DAMS IN THE DARLING RANGE

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ABSTRACT

Geotechnical factors play a major role in the design and construction of dams in the Darling Range east of Perth. These factors are described in relation to case histories for a number of water supply dams that have been constructed over the last one hundred years.

The Darling Range is underlain by the Archaean Yilgarn Craton, which consists of granitic and gneissic rocks that have been intruded in places by dolerites. Conglomerates of suspected Tertiary age occur at North Dandalup and Harvey Dams. The variable weathering in the granitic terrane requires special foundation and permeability control measures. In addition, weathering and ground water movements related to faults, shear zones and contacts contribute to adverse geotechnical conditions commonly found in the Darling Range. The effects of jointing, in particular the pervasive sheet joints, and the presence of corestones in foundation and cut-off excavations, are also described. Problems associated with natural construction materials used for dams in the Darling Range are outlined.

1 INTRODUCTION

Dams in the Darling Range are a primary source of water supply to the Perth Metropolitan area. There has been a wealth of design and geotechnical experience gained during just over one hundred years dam of construction in the Darling Range. However, much of the early work is not well documented. Many of the original structures are still in existence and in recent years they have been coming under increased review and scrutiny. These reviews have shown that the original dam builders had a very good understanding of the mechanisms of seepage and the need to keep the seepage under control. However, limitations of construction technology of the day have left a legacy of other problems. In the immediate post war years, improvements in construction equipment led to a surge in dam construction, but many of the projects failed to build on the knowledge that had been gained in the first half of the century. Extensive remedial works have therefore been required to some of these dams. In recent years, careful attention to the geotechnical problems at these sites has allowed successful completion of a large number of new projects and for a number of the older projects to be upgraded. This paper attempts to trace the historical context of this work and to look at the geotechnical factors that have affected the structures (listed in Table 1 and shown in Figure 1), and the solutions used.

2 HISTORICAL BACKGROUND

The first dam constructed in Western Australia was Victoria Dam, in 1891. This dam was a concrete gravity structure with a large radius arch shape in plan, constructed on Munday Brook, near Lesmurdie just east of Perth. The arch shape probably contributed little to the stability of the dam and although it lasted just on 100 years before it was decommissioned, the standards of construction left something to be desired. The geotechnical issues faced at the site reflected the general conditions found along much of the scarp, with zones of deep weathering, massive granitic rocks on the abutments with extensive development of sheet joints and the presence of dolerite dykes in the river valley.

The construction managers dealt with these issues in a thorough fashion, ensuring that foundation excavations were sufficiently deep, so that very little seepage was observed through the foundations. Timber piles were used to shore up the foundation excavation to depths of the order of 8m to 10m. However, the same care was not taken with the concrete mix design so that the structure finally deteriorated to the stage where it had to be decommissioned. The basic understanding of the nature of the geotechnical issues, particularly with regard to foundation materials and treatment, was typical of the construction for all the major dams built up until the mid 1950’s.

For the two major concrete gravity dams constructed in this early period, Mundaring and Canning Dams, the foundations were developed on slightly weathered to fresh granitic rocks. At Mundaring, a major dolerite dyke in the river course required excavation to a depth of more than 30m to reach an acceptable foundation level. Leakage through the foundations and foundation pore pressures are low. At Canning, the granitic rocks are more massive and relatively shallow foundation excavations were required, with the exception of localised deep zones adjacent to a dolerite dyke in the river channel.

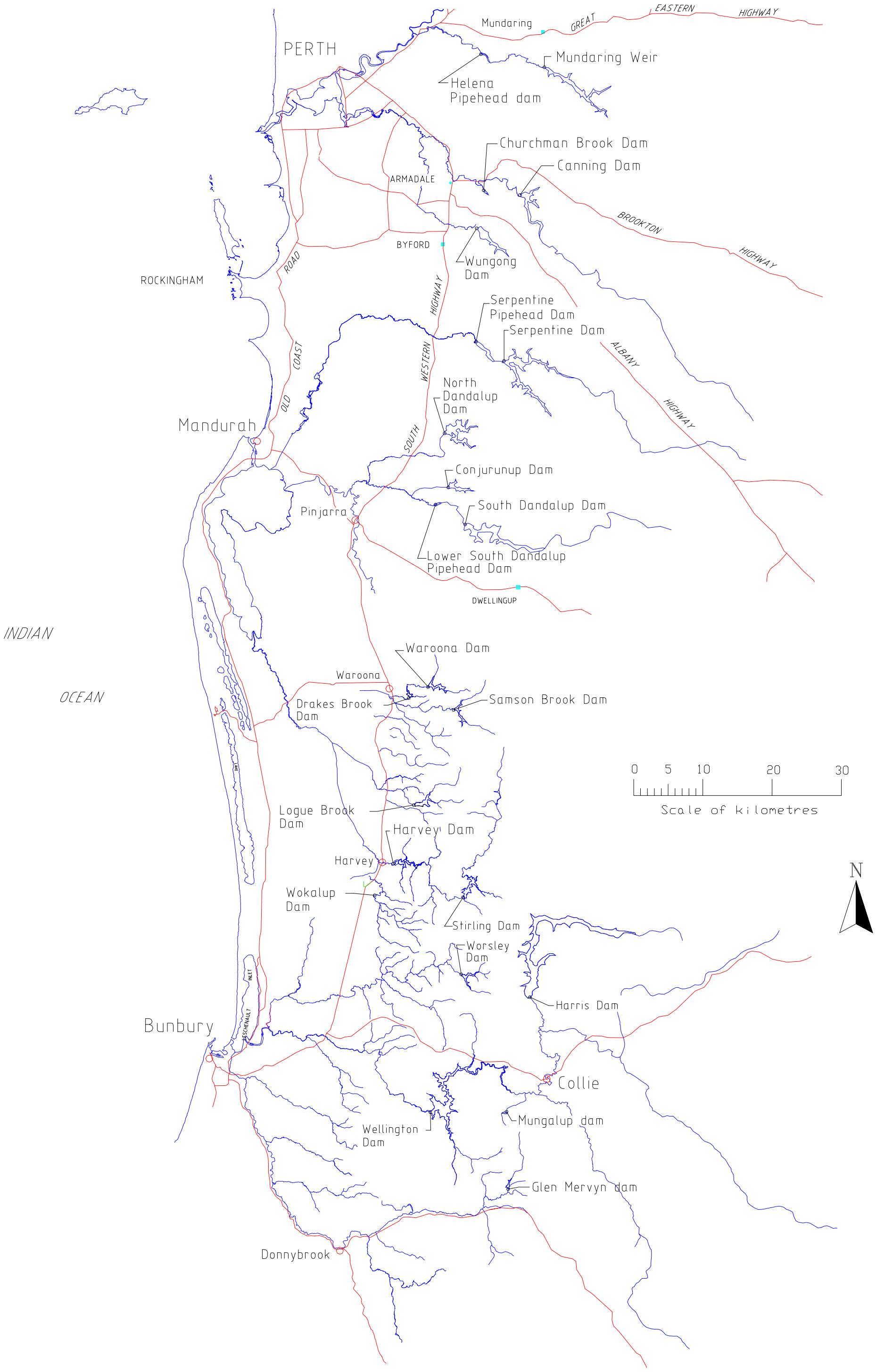

Figure 1: Locality Plan

Work at both Harvey (old) and Wellington concrete gravity dams proceeded with little impact of the foundation conditions on the design. At Harvey, the deeper weathering on the abutments lead to the selection of a composite earth and rockfill dam when the dam was raised in 1932. Wellington Dam was originally constructed in 1933 and was raised in 1960. Founded on massive granite gneiss, the dam foundation was shaped to optimise the dam construction. Deeper weathering on the left abutment led to a realignment of the crest in an upstream direction.

The only other major concrete gravity dam constructed around Perth was the New Victoria Dam, built in 1991 to replace the original Victoria Dam. The foundation conditions at the new site just upstream of the original dam included a major dolerite dyke down the middle of the river bed, extensive sheet jointing on the left abutment at depth and a major step in the foundation on the right abutment at the boundary between the dyke and the gneiss. Following extensive excavation of the foundation rock to achieve a foundation on slightly weathered to fresh rock, very low grout takes were recorded in the foundations. During concrete placement some post excavation stress relief of the foundation surface resulted in the need for further clean up prior to concrete placement.

The importance of geotechnical issues to dam construction is most vividly illustrated in the changes in construction of earthfill dams over the last century. The early major earthfill dams constructed in the period up to the end of World War II, such as Churchman, Drakesbrook, Samson and Stirling Dams, together with a number of other smaller dams (Mungalup, Hester and Williams) were all characterised by extensive treatment of the seepage cutoffs through the deeply weathered foundation. These were generally very successful in reducing seepage. However, the construction of the embankment fills occurred in a period of development of modern earthmoving techniques and has resulted in poorly compacted embankments without filters to protect against piping failures. Post construction settlement at Drakesbrook Dam is believed to have approached almost 8 to 10% of the embankment height.

In the post war period, from about 1950 to 1970, a number of dams were constructed using heavy earthmoving equipment and good compaction techniques, based on USBR criteria for seepage control and piping protection. On the more deeply weathered foundations, the construction of the cut-off was often left incomplete and in many cases no action was taken to increase seepage path lengths to reduce seepage. Almost a third of these dams required additional seepage control works following first filling. More recently, additional stabilisation works have been necessary to address issues of high pore pressures in the foundations, low embankment stability, potential foundation heave and upgrading of the piping protection works in a number of these dams. Many of the remaining dams have outstanding issues with excessive foundation pore pressures and high seepage losses.

The trend over the last three decades has been to construct dams with positive seepage control provisions. The improved understanding of the principles of geomechanics has led to the development of more effective piping control measures and construction on the deeply and variably weathered foundation materials. Where the foundation conditions are favourable, the use of earth core rockfill dams has replaced the use of homogenous earthfill dams that have been common in the past. This has been accompanied by more extensive processing of the fill materials, not only of the filters but also of the bulk fills, to reduce material variability and reduce construction risk.

3 GEOLOGY

The Darling Scarp, which is the surface expression of the Darling Fault, forms the boundary between the coastal plain sediments of the Perth Basin and the western edge of the Precambrian plateau (see Key Figures 1 and 2). The area to the east of and including the Darling Scarp (loosely referred to as the Darling Range) forms part of the Yilgarn block, a stable Archaean craton composed dominantly of granites, migmatites and gneisses, which have been intruded by dolerites. The geology and geomorphology of the Darling Range is described in other papers (e.g. Commander, 2003; Anand and Butt, 2003, this volume; Bulley and Masterson, 2003, this volume; Wyrwoll, 2003) and in previous publications (e.g. Wilde and Low, 1978; 1980; Geological Survey of WA, 1990; Myers and Hocking, 1998).

The Darling Range lies within a belt of variable gneissic rocks and basic igneous rocks that trends parallel to the Darling Scarp. The rocks have been subjected to episodes of intense deformation and high-grade metamorphism, accentuated by proximity to the northerly trending Darling Fault, a major geological boundary between the Pinjarra Orogen and the Yilgarn Craton to the east. The rocks in the zone adjacent to the fault are highly variable and have strong foliation, banding and other features associated with shearing of the rocks (such as mylonites). The effects of deformation related to the fault reduce eastwards and the rocks typically become more massive and uniform. The variable and sheared nature of the basement rocks (granite gneisses and metadolerites) has important implications with regard to their geotechnical conditions. Geotechnical conditions at dams near the Darling Fault (e.g. Harvey and Wokalup) are significantly different when compared to other recently constructed dams in the south west of the state, which are located further from the Darling Fault (e.g. Harris Dam, in excess of 20km from the fault).

Table 1: Summary of main dams and associated geotechnical issues in the Darling Range

Dam	Type	Date Comp	Issues
Victoria	55m high RCC dam	1891	Corestones, depth of weathering, dam decommissioned in 1991
Mundaring	70m high concrete gravity	1901	Dolerite in river bed, dam raised in 1951
Harvey (old)	20m high concrete gravity	1916	Dam raised in 1932, decommissioned in 2002
Bickley	Curved gravity dam	1926	Deep cut-off under main gravity wall, partial cut-off under abutment sections in deeper weathered material
Churchman Brook	Pug core earthfill	1928	Cut-off, deep variable weathering, pug clay core that is showing signs of piping failure
Drakesbrook	17m high earthfill	1931	Deep foundation cut-off, poor compaction of embankment with extensive settlement.
Wellington	37m high concrete gravity dam	1933	Dam curved to optimise fit onto foundations, deeper weathering on left abutment lead to a realignment of the axis.
Samson Brook	31m high earthfill dam	1941	Deep weathering across foundation, pug core cut-off, issues with lining of spillway
Canning	70m high concrete gravity	1940	Dolerite, sheet joints, AAR, grout contact
Stirling	53m high earthfill dam and tunnel	1946	Deep weathering, foundation cut-off wall
Serpentine	55m high earthfill	1961	Earthfill, dolerite, gneiss, sheet joints, cut-off
Logue Brook	49m high earthfill	1963	Deep variable weathering, foundation leakage under saddle dam
Waroona	45m high earthfill	1966	Deep variable weathering, foundation leakage
Glen Mervyn	20m high earthfill	1969	Combination of upstream positive seepage cut-off and upstream blanket has successfully controlled foundation seepage
Lower Helena	Concrete gravity	1971	Sheet joint joints and deep foundation excavation
South Dandalup	43m high zoned earthfill	1971	Deep weathering of dolerite under spillway, halloysite clays in embankment fills
Wungong	65m high earth core rockfill	1982	Landslide, weathering profile, dolerites, leakage in foundation
Worsley Freshwater Lake	31m high earthfill	1983	
Harris	37m high zoned earthfill	1990	Deep residual soils and foundations, slurry trench culvert, articulated culvert outlet works
New Victoria	52m concrete gravity dam (RCC)	1991	Deep weathering, differential weathering and impact on foundation shape, sheet joints, stress relief
Conjurunup	17m high concrete gravity dam	1992	Sheet joints
North Dandalup	64m high earth core rockfill	1993	Core stones within left abutment, conglomerate on saddle dams, extensive dolerite dykes through river bed, cut-off
Harvey (new)	45m high earth core rockfill	2002	Banded and variable weathering, sheared, conglomerate on left abutment
Wokalup	13m high concrete gravity	2003	Banded and variable weathering, shear zones
Samson Brook Pipehead	23m high concrete gravity	2003	Variable weathering, slope instability

Weathering of the bedrock has played a major role in defining the engineering properties of the materials on the Darling Range and Plateau. Weathering has resulted in the local formation of deep residual soils (soils derived from the in situ weathering and decomposition of rock) and a variable profile of weathered material overlying the fresh rock.

Conglomerates of the Harvey Formation occur at various locations on the Darling Plateau (Geological Survey of Western Australia, 1990). The conglomerates unconformably overlie the Archaean basement and are thought to be early Tertiary remnants of a previously extensive palaeo-drainage system (Geological Survey, 1990). They occur at North Dandalup and Harvey Dam sites, although the nature of the deposits was different at each of these locations.

Laterites occur extensively on the Darling Range and Plateau (Anand and Butt, 2003, this volume). Laterites can take the form of a caprock (generally best preserved on ridge or hilltops), or a lateritic soil.

4 GEOTECHNICAL FACTORS AFFECTING DESIGN

4.1 VARIABLE WEATHERING PROFILE

The basement rocks are subject to highly variable and deep weathering conditions, particularly in the zones adjacent to the Darling Fault, which have been subject to intense shearing and as result, are strongly banded and foliated. The metadolerite dykes and micaceous or feldspathic gneiss bands tend to be more susceptible to weathering and form more deeply weathered zones of lower strength material. Contact zones between dykes and adjacent gneisses are likewise subject to deep weathering and groundwater movement. Foundation excavations commonly have an irregular and stepped profile, as a result of the differentially weathered bands.

Many of the dams in the Darling Range are constructed on deep residual soils that extend up to about 35m in depth, as for example at Harris Dam (Somerford et al, 1991), Churchman Brook Dam and North Dandalup.

The two key issues that arise in the deeply weathered soils are control of flow through the foundations under the dam embankment (not only to minimise the loss of water but more importantly to control pore water pressures, particularly in the downstream foundation) and the potential for piping. These issues are dealt with in more detail in the next section (4.2).

Potential foundation settlement has also been a significant issue on some of the dams that have been constructed on deeply weathered foundations. On most of the foundation materials derived primarily from granitic rocks, the soils are often relatively stiff. However there have been some notable exceptions. At Scabby Gully Dam near Manjimup, a small homogenous earthfill dam built on 20m of residual white clayey soils, problems with excessive seepage through the foundations required the construction of a toe drainage and weighting. However, excessive settlement resulted in the failure of the concrete encased steel outlet main some three years after the dam was completed. The outlet had to be decommissioned and a new high level siphon offtake constructed.

At Harris Dam, the investigations revealed deep soft foundations that were believed to be of alluvial origin. The dam is of the order of 37m high and an analysis of the foundation settlements indicated that movements of the order 600 to 800mm could occur during construction and additional settlements of the order of 25 to 30% more could occur during the longer term. Apart from the control of flow through the foundations, the main structural element that was likely to be seriously affected by this settlement was the outlet works. The solution selected was to construct the outlet culvert in articulated sections to conform to the shape of the settlement profile and to lay two DN 750 steel outlet mains within the culvert. The actual settlement observed during construction was of the order of 660mm and this has since increased over the last decade to a total of almost 900mm. One of the other points that was noted during the construction phase was that most of the downstream foundation was founded on very soft, extremely weathered doleritic materials and were probably responsible for the low strengths and large settlements.

At Wungong Dam the concrete lined spillway chute on the right hand side was designed to be constructed on fresh to slightly weathered rock excavated as a side cut down the abutment. As the excavation proceeded, excessive depths of weathered materials were found, with the increased depths particularly marked on the downhill side of the side cut. The solution in this case was to continue the excavation and to backfill with concrete before constructing the chute lining.

At Serpentine Dam the original spillway excavation had also been cut down to fresh to slightly weathered rock as a side cut on the right abutment. However the variable weathering profile had reduced the available freeboard in many locations and closely spaced open sheet joints containing weathered materials were rapidly eroded when the spillway first operated, resulting in the loss of many thousand of cubic metres of soil and rock (Figure 2). Remedial works consisting of partial lining of the chute were carried out and the spillway was tested the following year. A feature of the test was the significant erosion of the downstream end of the chute due to plucking of blocks from the sheet jointed rock mass. With later reviews of the hydrology resulting in much larger flows being predicted, the decision was made to deepen the spillway to minimise the risk of loss of the downhill side wall due to back erosion in the variable weathered materials and the along sheet joints. Such a failure could have potentially led to the loss of the main dam embankment.

Dykes, and their contacts with the more widely distributed granitic rocks, are a significant feature of the Darling Range. In many cases when the foundations are opened up, the watercourse has been found to follow the strike of a dolerite dyke. In many cases after appropriate excavation and treatment, the dolerites have formed excellent foundations. Some notable exceptions have occurred at Mundaring Dam, where CY O'Connor reported that foundation excavation to a depth of more than 30m was required to achieve a suitable foundation in the weathered dolerite.

At South Dandalup Dam, the spillway on the right abutment was constructed running obliquely down a major dyke structure. The excavation shape was such that it was possible to site the spillway crest and a short section of chute on slightly weathered to fresh dolerite, but the balance of the chute was constructed on material that ranged from highly to extremely weathered dolerites of an open texture and low density. The solution adopted to stabilise the chute was to leave this material in place and to construct a comprehensive under drainage system combined with passive rock anchors to manage the loads on the chute.

Figure 2: Serpentine Dam – Deepening of the spillway chute (2002) shown on the photograph on the left. The original invert of the unlined chute was at the level of the berm on the left hand side of the photograph. The photograph on the right shows the granite weathering profile. The original floor of the spillway chute was at the top of the cutting on the left of this photograph.

At Canning Dam the foundation consisted of relatively massive granite, with a dolerite dyke in the river section. While sheet joints were present these were excavated to a suitable foundation and relatively little seepage penetrates them. The dolerite dyke (approximately 6m wide) within the central foundation, was treated during construction along the contacts with the granite by deeper excavation, grouting and concrete backfilling. However when investigations of foundation pore pressures were undertaken during the 1980's, a zone of high pressure was identified in the downstream foundation. This was initially presumed to be coming through deep sheet joints. Further investigation indicated that the seepage occurred along the contact zone between the granite and the dolerite. Investigation holes drilled through the margins of dykes effectively relieved the excess pore pressure. Remedial works included draining the interface with pressure relief boreholes, resulting in a drop in pore pressure of more than 8m in the downstream foundation.

4.2 PERMEABILITY

The permeability of the deeply weathered foundation materials has been a cause of considerable difficulty for dam foundations. Back calculation of the foundation permeability based on measured flow rates and gradients has indicated an average rock mass permeability as high as 10^{-5} m/sec on a number of sites. This permeability is primarily caused by flow through relic joints in the rock mass, zones of less weathering, and along the boundaries of geological features. The key problem caused by the seepage through the foundations has not been limited to the loss of water, but is primarily the embankment instability, piping and increased risk of foundation heave or blow out caused by the high pore pressures in the downstream foundation.

At Harris Dam, where pump testing confirmed that high foundation permeabilities of the order of that quoted, the solution adopted was to construct a slurry trench up to 26m deep across the entire foundation. This solution was not dissimilar to the full depth pug clay cutoffs that had been constructed with the dams in the first half of the 20th century. The slurry trench in combination with an upstream impervious seepage control blanket was successful in reducing seepage rates from the initial expected value of 5 to 10 l/sec to the current value of 2 l/sec.

Upstream impervious blankets are one of the few relatively economical methods available to reduce seepage flows in existing dams. They are used to extend the seepage path lengths and reduce the hydraulic gradients. They have been effective in reducing seepage flow rates by up to about 50%, but as the length of the blanket increases, the effect of flow through the blanket becomes more important. Typically blankets have been designed to achieve gradients of about 10%, the seepage path length at top bank level being designed to be 10 times the maximum height of the dam.

At Manjimup Dam the construction of a clay blanket was successful in reducing total seepage by almost 60%. Since that time, upstream impervious blankets have been included in the construction of six new dams and have been retrofitted to another four dams. The most recent of these was at Waroona Dam, which has had a long history of seepage related problems. Initial indications are that the blanket has been successful in reducing seepage by about 50 to 60%.

Chemical grouting has been used on at least one occasion to reduce the permeability of weathered foundation materials. Worsley Alumina Pty Ltd (WAPL) constructed a chemical grout cut-off beneath the foundation of some of their containment dams during the initial establishment of the project in the early 1980's. A three-line curtain was constructed for the full depth of the weathered profile. This was reported to have been successful in reducing the permeability of the foundation materials to less than $1x10^{-6}$m/sec. There has been some reluctance to use chemical grouting on the grounds of adverse impacts on potable water quality.

The treatment of the problems at the downstream toe has generally included measures such as drainage wells, sandwich filters and toe weighting. The problem with these systems is that the filter and drainage elements tend to block with iron oxide precipitates where the seepage waters are exposed to oxidation on exposure to the air. Complete blockage of the drainage system at Waroona Dam was noted during the remedial works. The earthenware pipes were completely blocked and the surrounding gravel filter media was highly contaminated (Figure 3). Such drainage systems need to be designed so that they can be cleaned and the filter grading needs to be coarse enough to minimise the risk of becoming clogged.

Figure 3: Waroona Dam – Photograph on left showing blockage of the old GEW drainage pipes and the high degree of contamination of the coarse filter media surrounding the pipes. Photograph on the right shows the construction of sandwich chimney filter system consisting of coarse aggregate sandwiched between sand at Waroona Dam in 2002.

Piping protection is usually provided by a sand filter, of which there are ample supplies available on the coastal plain. The close proximity of these materials to the dams means that supplies are relatively cheap. The finer grained sands from the Bassendean Formation usually have a D_{15} size of 0.1 to 0.2mm, making them good filter materials to control piping. However, the relative paucity of coarse river gravels means that the coarse filters are normally provided by a crushed rock material that is screened, washed and recombined.

Weighted sand blankets on the toe are rarely successful, as the sand can have a permeability lower than the foundation materials, resulting in an extended seepage path and increased seepage pressures at the toe. To be successful such filter blankets need the sand materials to provide piping protection, but should be overlain by a coarse crushed aggregate. Figure 3 shows a typical sandwich filter treatment under construction at Waroona Dam.

4.3 CONGLOMERATES, DEEP WEATHERING PROFILE AND BEDDING PLANE JOINTS

Conglomerates of the Harvey Formation occur at various locations on the Darling Plateau (Geological Survey of Western Australia, 1990). At Harvey Dam (new), deeply weathered conglomerates have been found on the upper left abutment and along the southern side of the reservoir. The contact surface with the underlying basement gneisses is highly variable and irregular, as indicated by rapid variations in depth to the contact. The contact has been measured in boreholes to depths of up to 62m below ground level. The conglomerates at Harvey Dam have been subdivided into two main types, an upper and a lower conglomerate, with a transitional intermediate zone.

The upper conglomerate horizons consist of a fine matrix containing scattered rounded clasts of quartz and granite. This horizon can be in excess of 10m thick at the site. The upper conglomerate unit has only been observed as a residual soil at Harvey. The lower conglomerate horizon consists generally of abundant angular to sub-angular clasts (gravel, cobbles and boulders up to about 1.5m in diameter) of granite gneiss, metadolerite, feldspar and quartz fragments in a matrix of lithified silty sandstone. The fresh conglomerate is generally massive and unjointed in nature, and forms a low to medium strength rock (Figure 4).

Figure 4: A core sample of the conglomerate from Harvey Dam, indicating clasts of granite and dolerite in a sandstone matrix.

The rounded and highly resistant nature of the clasts in the upper conglomerate unit indicates that it is probably of fluvial origin. The generally angular and variable nature of the clasts in the lower conglomerate unit suggests that it was originally of colluvial origin (comprising scree and possibly landslide debris), that has subsequently been lithified to form a weak rock.

The original borehole investigation of the upper conglomerate material showed that the upper zones had been extensively lateritised but showed no apparent signs of bedding defects, although a number of variable perched water tables were observed. When the excavations were opened up, a widely spaced set of sub-horizontal bedding plane surfaces and rare oblique joints were observed. The bedding surfaces showed signs of slickensiding. Shear box testing showed that at a value of 17^{o}, the shear strength of the bedding planes was considerably lower than the parent soil, which had tested at shear strengths of 28 to 34^{o}. The bedding planes also acted as preferred seepage paths, accounting for the presence of the perched water tables (Figure 5).

The weathered conglomerate rock is subject to deterioration and slaking on exposure to the atmosphere, following excavation, as indicated by break down of samples wetted prior to Unconfined Compressive Strength testing. The soils derived from the upper conglomerate material were used extensively for earthfill materials for the construction of Harvey Dam, for core materials for both the rockfill embankment and the zoned earthfill, and for shoulder materials for the zoned earthfill embankment. Variation in material properties through the profile was overcome by stockpiling and mixing of the materials during the excavation and handling processes. In the borrow pit, the plasticity index (PI) of the materials averaged 25 to 30%, but after stockpiling this increased to 40 to 45% when placed in the embankment.

Figure 5: Cut-off trench through upper conglomerate at Harvey Dam (2001), photograph on left showing failure of sidewall along bedding plane surface and steeply dipping joint. Photograph on right showing underside of bedding plane surface.

Conglomerates also occur at North Dandalup Dam where they were encountered in the cut-off trench for the saddle embankment dam (Marcos 1986; Mather, 1993). The conglomerates at North Dandalup form a soil and do not appear to be lithified (in contrast to Harvey Dam). In addition, at North Dandalup the conglomerates consist of loose clasts of large subrounded boulders of gneiss and dolerite, with a small proportion of clayey matrix. The clayey near-surface materials proved to be highly dispersive, giving rise to issues with the design of filters for the embankments and concern that if these materials were exposed to the reservoir, significant increases in turbidity could occur. The solution to this latter problem was to construct an impervious non-dispersive clay blanket over the exposure of conglomerate within the reservoir basin. This appears to have successfully controlled any adverse impacts on water quality.

4.4 SLOPE STABILITY

Colluvial and residual soils overlying the basement rocks are subject to slope instability, particularly in areas of deep soils and poor drainage. The spillway approach channel and right abutment areas at Wungong Dam have a history of slope instability and landslides, which resulted in delays and extensive remedial measures during construction in the period 1976 to 1979. A major portion of the upstream side of the cuttings in the spillway approach consists of an existing landslide. This has been widely reported on previously (e.g. Marcos, 1978, 1984; Lilly, 1986; Fell et al, 1992).

Following initial site investigations for the dam in 1973, the dam axis was rotated to bring the right abutment and spillway downstream of a suspected old landslide. Despite this, four landslides occurred on the right abutment during the construction period in 1977 to 1978. The fourth and largest slide (known as the Fourth Slide, with a volume of about 100,000 m^3), cut through the spillway approach channel and moved into the downstream rockfill and filter zones (Lilly, 1986). The basal failure surface of the slide in the foundation area consisted of micaceous clayey silt, probably a weathered and sheared basic dyke. Remedial measures to the spillway cuttings during construction included excavation of two bench levels and cutting the slopes to a batter of between about 1:1 to 0.75H:1V. Rough, unlined drains were excavated at the crest of the slopes and on the benches. In addition, the rockfill foundation was excavated to below the sheared basic dyke seam level and the slide was stabilised by a spur of rockfill that projects from the dam shoulder.

4.5 FAULTS, SHEAR ZONES AND JOINTS

Faults and shear zones occur commonly in the foundation and spillway excavations for a number of dams. The faults result in deep weathering, closely jointed and broken material and groundwater seepage. They can therefore have a major impact on foundation conditions and depths and permeability of the dam foundations.

The Darling Fault is a major geological boundary that separates the Pinjarra Orogen and the Yilgarn Craton. The most recent activity along the fault is thought to have occurred between early Silurian and early Cretaceous times (Geological Survey, 1990). This activity was however preceded by a long history of tectonic movement in the Darling Fault Zone during the Precambrian, which resulted in intense deformation (cataclasis) of the gneisses in a variable zone that extends to the east of the fault. The deformation has been responsible for the development of a strong foliation and banding in the gneisses and the development of cataclastic features such as mylonites (zones of intense fracturing and crushing of the rocks, to form a fine-grained material) and shear zones. Of significance is the presence of slickensiding, which has been identified on some joints and shear surfaces, particularly in the contact zones with metadolerites. A number of distinct linear features are apparent on landsat images and aerial photographs of the Darling Range and South-West Region. In particular, a number of distinct and extensive features trend in a north-westerly direction (such as the Darkan Fault near Perth, Kojonup Fault, Tenterten Fault and Boyup Brook Fault, Myers and Hocking, 1998). These features provide a strong structural control to rivers in the Darling Range. A distinct linear feature, probably a fault, extends along the Churchman Brook and Canning River and passes through the Churchman Brook dam site. This fault is suspected of being responsible for the particularly deep weathering and extensive iron oxide staining that occurs below the dam.

The faults result in deep weathering, closely jointed and broken material and can therefore have a major impact on foundation conditions and depths and permeability of the dam foundations. Two sites that have been constructed within 2km of the Darling Fault are Harvey and Wokalup Dam sites. The Wokalup site particularly was characterised by highly sheared and banded gneissic rocks, with bands of schists and metadolerites (Figure 6). Shearing and faulting parallel to the banding in the gneiss resulted in deeply weathered and highly fractured zones. The schists and the metadolerites also tended to be more deeply weathered. The presence of a highly sheared and fractured zone on the downstream toe at Wokalup resulted in the dam axis being rotated upstream to locate the dam on more favourable foundations.

The foliation and banding of rocks in the Darling Range typically trend north to north-east with a steep to sub-vertical dip. Joints and contact zones associated with the foliation and banding are frequently planar and continuous over large distances (Figure 6). Slickensiding, indicating movement along the joint or fracture surfaces, occurs along some foliation surfaces and contacts. Preferential weathering also occurs along contact zones and associated joints, with the development of clayey weathering products and commonly chlorite.

Sheet joints are joints associated with stress relief and are orientated sub-parallel to the ground surface. The intensity and frequency of these joints diminishes with depth from the surface. At shallow depth, sheet joints are a characteristic defect in the granitic terrain and are commonly continuous, and contain zones of highly or extremely weathered material and joint infill. Joint surfaces are commonly rough or stepped and irregular. The sheet joints have important engineering implications, as they can occur below the slightly weathered to fresh rock surface and therefore below the level of foundation or cut-off excavations for the dam or the floor of spillway, where they can act as flow paths. Foundation or cut-off excavations should therefore be taken below the level of significant sheet joints.

Figure 6: Wokalup Dam (2003) site showing the intense foliation and banding in the gneisses close to the Darling Fault.

4.6 CORESTONES

The presence of corestones of hard granitic rock or dolerite within residual soils can present engineering problems in the Darling Range. Corestones display spheroidal weathering features and are formed by preferential weathering of joint bounded blocks of fresh to slightly weathered rock (Fell et al, 1992). Corestones can form significant obstructions in foundation excavations or in cut-off excavations for dams. Extensive zones of corestones were encountered in the cut-off trench and embankment foundation excavations (Figure 7) on the lower left abutment at North Dandalup Dam (Waters and Dart, 1999). The corestones varied in size from half a metre to massive boulders the size of a room. The corestones were surrounded by extremely weathered material and had to be removed from the excavations by local blasting and additional excavation, to expose the underlying undulatory, slightly weathered to fresh bedrock surface. This resulted in delays to the construction program and deeper excavations than originally anticipated.

Figure 7: North Dandalup Dam, the corestones on the left abutment (see photograph on the right) caused considerable difficulty in preparing the foundation for the earth core and the rockfill zones of the embankment.

Corestones were also encountered in the excavations for the slurry trench at Harris Dam (Somerford et al, 1991). Depending on the size of the corestones, they were removed using the clamshell grab or by deviating the alignment of the slurry trench around the obstruction. Where the core stone was too large to deviate the slurry trench, it was sometimes necessary resort to blasting or in extreme cases, to extensive grouting around the corestone.

4.7 GROUND WATER

Seepage of groundwater into excavations is a common problem during construction of dams in the Darling Range. In particular, seasonally perched water tables occur intermittently on valley sides. The perched water table generally occurs at shallow depth and is often associated with underlying residual soils of lower permeability. Zones of surface seepage are often associated with hydrophilic vegetation such as sedges and reeds. Seepage within the bedrock can occur along joints (particularly sheet joints), faults and contact zones. This has resulted in a requirement for dewatering in foundations and cutoff areas for most dam projects.

4.8 IMPACT OF DISPERSIVE SOILS AND HALLOYSITE ON CONSTRUCTION MATERIALS

Soils derived from the weathered rocks of the Darling Range are widely used for the construction of embankment dams in the south west of the State. Materials selected from these weathered materials make excellent construction materials and have relatively low permeability. However care has to be taken in selecting the materials to be used as there are significant variations with depth, the surface zones often being highly ferruginised, whereas with depth, the deposits become less weathered, and often with more silt like properties. Residual soils derived from the granitic materials are normally selected, having low to moderate plasticity. However, the borrow pits are often dissected by dolerite dykes and schists, which form residual soils of high plasticity and potential expansiveness, making them relatively unsuitable for construction. Corestones and variable weathering can also affect the shape and profile of the borrow pit.

On a number of recent projects the strategy that has been adopted to overcome the variability of the materials has been to stockpile all the material, excavating from the full depth of the pit when delivering to the stockpile and excavating from the full depth of the stockpile when transporting to the embankment. This has the effect of reducing by up to 80% the variability in the index properties, making moisture control and compaction much easier to control. A feature of the conglomerate materials used at Harvey Dam was that the soils were apparently a mixture of both the granitic and the doleritic soil types, hence the relatively high PI’s of the construction materials derived from this source.

Dispersive soils deflocculate in water and are therefore predisposed to erosion and piping, which is of particular significance to embankment dams. Soils containing a high proportion of smectite and illite clays are particularly susceptible, as a result of repulsive forces between clay particles. The following tests are commonly used (amongst others) in WA to determine the dispersivity of the soils:

- Emerson class number, according to Australian Standard AS1289.3.8.1
- Pinhole test, according to Australian Standard AS1289.3.8.3

In addition, the Hole Erosion Test (HET), as developed by the University of New South Wales, is used to assess the erodibility of soils. Laboratory testing carried out on residual soils, for use in construction of embankment dams, indicate notoriously variable results. However, it appears that in the generally high rainfall Darling Range area, the residual granitic soils do not generally present a problem, but localised zones of potentially dispersive material can occur. However, it should be noted that granitic soils in other parts of the region and worldwide can be highly dispersive (e.g. Brink, 1979). The residual dolerite soils can also be potentially dispersive. The dispersive properties of the soils, as applied to water retaining structures, should therefore be assessed as a matter of routine during site investigations.

The clay mineral halloysite is known to exist in the residual soils derived from the granitic/gneissic rocks of the Darling Scarp (Lilly 1979, Marcos 1984). Its presence is indicated by unusually high sample moisture contents, coupled with much lower than average dry densities or by a difference between moisture contents carried out at low temperature (approximately 45° C) and high temperature (105° C, in accordance with the normal testing procedure). These unusual properties are due to the loss of water molecules from the crystal structure of the clay as the sample is heated during moisture content testing. This results in a greater weight change in the sample than would ordinarily occur when only the water from the pores is evaporated during the oven drying process. The presence of halloysite in the residual soils does not impact on the shear strength or compaction characteristics of the soils and will have little or no impact on the design or implementation of the earthworks. However, the testing procedures have to be modified to use wet density testing procedures such as the Hilf test for compaction control.

4.9 ALKALI AGGREGATE REACTION

Granite and dolerites are widely used as sources of concrete aggregate in the Darling Range. There is evidence however that deformed and metamorphosed granite/gneiss can lead to alkali aggregate reactivity. In the concrete works on dams this can manifest itself in the early stages as widespread hackley cracking patterns. These can develop quite quickly, certainly within a decade of the initial construction, in some cases. As the cracking develops it can result in splitting of the concrete sections, as has occurred at Harvey weir (old) in the core wall and on the spillway training walls at South Dandalup Dam.

Figure 8: Canning Dam, the photograph on the right shows the extensive cracking in the region of the upper gallery, believed to have been caused by AAR.

Concrete gravity dams typically tend to expand and appear to move upstream under the influence of alkali-aggregate reaction (AAR). Typically the reaction results in an expansion of the downstream face. At Canning Dam, a 70m high concrete gravity structure the dam has moved upstream by 1.25mm per year and risen vertically by 0.95mm per year. The top of the crest tends to rotate towards the upstream about a centre located near the long-term mean water level on the upstream face. This suggests that the AAR below the water line is less active.

Canning dam had also been subject to considerable cracking of the upper parts of the dam and upper gallery (Figure 8). Investigations have shown that the cracking was due to a strong AAR in the concrete, which has been related to the presence of deformed granite and gneiss aggregate (Shayan et al, 2000). Petrographic examination of the aggregate shows it to contain quartz crystals with undulose extinction and microcrystalline quartz along grain boundaries, which are indicative of potential for alkali aggregate reactivity.

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6 REFERENCES

Anand, R and Butt, C. (2003). Distribution and Evolution of Laterites and Lateritic Weathering Profiles, Darling Range, WA. *Australian Geomechanics J.* Vol 38 No 4 (This Volume).

Blight, G.E. (Ed), (1997). *Mechanics of Residual Soils*. AA Balkema, Rotterdam.

Brink, A.B.A. (1979). *Engineering Geology of Southern Africa.* Building Publications, Petoria.

Commander, P. (2003). Outline of the Geology of the Perth Region. *Australian Geomechanics J.* Vol 38 No 3.

Bulley, B. and Masterson, S. (2003). Precambrian rocks of the Darling Range, Perth. *Australian Geomechanics J.* Vol 38 No 4 (This Volume).

Fell, R., MacGregor, P. and Stapledon, D. (1992). *Geotechnical Engineering of Embankment Dams*, AA Balkema, Rotterdam.

Geological Survey of Western Australia (1990). *Geology and Mineral Resources of Western Australia*: Western Australia Geological Survey, Memoir 3.

Lilly, R.N. (1979). Wungong dam design and construction. *Inst. of Engineers, Aust. Diamond Jubilee Conf.*, Perth. Paper Event No. 306-1.

Lilly, R.N. (1986). Wungong Dam Landslide. *ANCOLD Bulletin*, No 74

Marcos, G. (January 1978). Wungong Dam - A brief geological report of landslides in the right bank. Geological Survey of WA, Engineering Geology Report EG 191.

Marcos, G. (1984). Wungong Dam. Geology of construction area. Geological Survey of Western Australia, Engineering Geology Report EG277, Volume 1.

Marcos, G.W. (1986). North Dandalup Dam Site Ground Investigations, Geological Report. 3 volumes. Geological Survey of WA, Engineering Geology Report 316.

Mather, R.P. (1993). North Dandalup Saddle Cut-off Trench Geological Record of Construction. Report to Water Authority.

Myers, J.S. and Hocking, R.M. (1998). *Geological Map of Western Australia*, 1:2,500,000 (13th Edition). Western Australia Geological Survey.

Shayan, A., Wark, R. and Waters, J. (April 2000). Investigations on Canning Dam Concrete Gravity Structure and its rehabilitation. *ANCOLD Bulletin* No. 114.

Somerford, M., Davenport, F. and Brice, S. (1991). Geotechnical aspects of the design, construction and performance of the Harris Dam. *ANCOLD Bulletin* No. 88, p. 33 – 53.

Waters J and Dart W, (1999). North Dandalup Dam and Appurtenant Works, Construction Report. Internal Water Corporation report.

Wilde, S.A. and Low, G.H. (1978). *Perth Western Australia*, 1:250,000 Geological Series Map and Explanatory Notes. Geological Survey of Western Australia.

Wilde, S.A. and Low, G.H. (1980). *Pinjarra Western Australia*, 1:250,000 Geological Series Map and Explanatory Notes. Geological Survey of Western Australia.

Wyrwoll, K-H. (2003). The geomorphology of the Perth Region, Western Australia. *Australian Geomechanics J.* Vol 38 No 3.