Challenges in dam design on lateritic soils

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The Western Australia Water Corporation plans to increase the storage capacity of Millstream Dam, which is located near Bridgetown in the south west region of WA. The existing dam is an 18 m high zoned earthfill embankment constructed in 1962. The dam suffered a block heave of the foundation at the downstream toe during the first filling, probably attributable to high foundation pore water pressures. The dam upgrade will be challenging due to complex and unfavourable foundation soils coupled with these artesian pressures.

The dam is founded on lateritic soil, which is a common weathering profile throughout the region. These soils formed in a tropical environment of fluctuating water tables, severe leaching and translocation of iron oxides over many millions of years. As a consequence some of the lateritic horizons at Millstream Dam have been modified such that they exhibit behaviours that are not consistent with conventional constitutive models and correlations. These are attributed to a complex structure of the soil microfabric, which comprises clay particles bonded together into larger aggregates. The clayey aggregates are also bonded to each other, forming a porous matrix of silty or sandy appearance characterized by low dry density and high void ratio, which may nevertheless disintegrate on working.

Comprehensive geotechnical investigations and extensive laboratory testing have revealed that the foundation materials display characteristics of clayey and granular soils. Under shearing, these soils demonstrate high initial strength, which gradually reduces as the inter-aggregate bonds are broken and the relative position of the aggregates changes. Several soil samples also exhibited significant contractive behaviour on shearing generating high pore pressures under undrained conditions.

This paper presents the investigation and design methods used in the foundation design of the Millstream Dam upgrade with emphasis on unusual behaviour of the foundation media.

Keywords: dam raising, lateritic soils, clay aggregates, aggregate bonding, strain softening

Introduction

Laterites are materials derived from extreme weathering of rock under tropical or semitropical climates. The term was originally used for a group of soils that quickly harden in air and were therefore suitable for construction of houses in southern India (Edgar, 1913). This quality also gave the soils their name, as in Latin "*later*" means a brick. The original definition was later broadened and used to describe soils in the weathering profiles of the present or ancient tropical regions (Millot, 1964). To date, many definitions of laterite soils have been published based upon appearance, weathering process or mineralogical composition (e.g. Maignien 1966, Tardy 1997).

For the purpose of this paper, a definition used by Gordon (1984) has been adopted and a laterite profile is herein defined as a complete sequence of ferruginous soils, from the fresh rock to topsoil, formed by the decomposition of the parental bedrock under the influence of fluctuating water tables in a warm savannah climate.

Under this broad definition, laterite soils are common in many areas in Africa, South America and Australia and cover approximately one third of the Earth's dry land (Tardy, 1997). They are in fact the most widely distributed sources of natural road gravels in the world.

This paper is concerned with the engineering properties of a laterite profile at Millstream Dam and the design of the upgrade works including the foundation treatment. The micro-mechanical properties of the Millstream Dam foundation soils are further discussed in Herza et al (2010).

Project background

Millstream Dam is located approximately 250 km south west of Perth. It is an 18 metre high zoned earthfill embankment completed in 1962. For more than 40 years the dam has been the primary source of potable water for the towns of Bridgetown, Hester and Boyup Brook.

During the first filling in August 1962, a block of soil about 4m by 5m in area immediately downstream of the dam toe was vertically sheared and water was observed to be discharging along the joints. This incident led to the installation of a weighting berm and pore-water relief wells at the dam toe. Following an increase of the foundation pore water pressures in the 1980s, an upstream clay blanket was installed in 1988.

The dam owner and operator, Water Corporation of Western Australia, is planning to upgrade Millstream Dam to double the available storage capacity to 1 GL and improve the safety of the dam. SKM has been engaged by the Water Corporation to undertake the design of the proposed dam upgrade. Prior to the proposed augmentation, consideration was also given to the construction of a new dam downstream of the existing dam with a larger capacity. However, the larger dam was found economically unattractive.

The proposed dam upgrade includes 5 m raising of the embankment crest, construction of a new outlet pipe through the left abutment and construction of a new spillway at the left abutment.

Site geology and lithology

Millstream Dam is located within the southern part of the Balingup Metamorphic Belt in the south-western portion of the Yilgarn Craton. The local geology is very complex comprising quartz-feldspar-biotite gneiss interleaved with large areas of quartz-feldspar-biotite granofels and thin units of quartzite, banded iron formation, quartz-mica-kyanite schist, calc-silicate gneiss, amphibolite and ultramafic rocks (Bamblett 2010).

The weathering (laterization) of the rocks in the Yilgarn Craton was a long process of mechanical breakdown and chemical decomposition that commenced in the Tertiary period (approximately 35 million years ago). Typical layering of the laterite profile is discussed in Anand and Paine (2002). Generally, this comprises weathered and bleached bedrock at the base, a clay-rich pallid zone, in places mottled and a ferruginous, and a siliceous or bauxitic upper zone. Cornelius et al (2006) point out that the secondary leaching, erosion and deposition of minerals has increased the complexity of laterite profiles in many parts of the craton, including the vicinity of Millstream Dam.

The modified laterite profile at Millstream Dam has been divided into several distinctive lithological zones and the following description was adapted from Bamblett (2010).

The upper part of the profile comprises residual pisolitic or nodular gravel in a sandy matrix, and/or an indurated pisolitic or massive *ferricrete (caprock) horizon*. This is underlain by a nodular *mottled zone* (Lam) comprising segregations iron oxyhydroxides, in a matrix of paler kaolinitic clay. The iron oxide mottles may have sharp, distinct or diffuse boundaries.

The mottled zone grades downward into a pale-coloured, *pallid zone* (Lap) composed essentially of kaolinite and quartz. This zone has neither the relict fabric of the underlying *saprolite* (Las) nor the mottles, nodules or pisoliths typical of the mottled zone. The saprolite comprises weathered bedrock in which the fabric of the parent rock is retained. It is generally coarser grained, of higher permeability and lower in-situ (dry) density than the overlying pallid zone material. This zone is referred to by Gordon (1984) as the *zersatz zone* and typically includes a lower coarse grained (sandy) horizon of high permeability. This directly overlies moderately weathered to fresh bedrock, with the transition to fresh material being often quite abrupt. It consequently acts as a perched aquifer, since the fresh rock is nearly impermeable.

During subsequent erosion since the Tertiary period the laterite profile at the Millstream Dam site has been extensively eroded. Much of the profile has been removed throughout the lower right abutment and downstream of the existing dam site.

The intensive leaching has formed a continuous horizon of highly permeable silty sands (Lsm) that occurs as a sub-horizontal layer directly underlying the pallid zone. This pervious layer exists throughout the centre and lower right abutments of the existing dam, and is thought to terminate at the surface (‘daylight’) some 200m downstream of the dam. It conducts water under elevated pressures is very likely responsible for the elevated piezometer pressures noted in 1962.

The pressurised Lsm zone has affected the adjacent materials through a process of fluctuating pore pressures and intensive leaching. The affected lithological units are: the lower pallid zone (Lapl), which is above the Lsm; and lower laterite zone (Lal), is below the Lsm.

A typical section of through the existing dam in the deepest part of the valley is presented in Figure 11.

Ground water regime

Subsurface flows at Millstream Dam are very complex and influenced by both the reservoir storage fluctuations and the movement of natural groundwater in the abutments. The ground water regime was investigated using water chemistry tests and measured pore water levels as part of the engineering design of the dam raising (SKM, 2010).

In general, three seepage paths were identified at Millstream Dam, namely: in the Las zone at the left abutment; through the Lsm zone under the centre of the dam; and along the slightly weathered to fresh rock interface.

Water chemistry test results and piezometer readings demonstrated that the seepage water in the left abutment originates from the reservoir.

The coefficients of linear regression between the reservoir water levels (WSL) and readings from two piezometers (EPZBH1_04 and PZBH04_04) at the left abutment (Figure 1) were found to be 0.4 and 0.25, respectively. Both piezometers show high correlation to the reservoir level (r^2 = 0.85). The high linear regression and correlation coefficients indicate a relative high permeability foundation material at the right abutment.

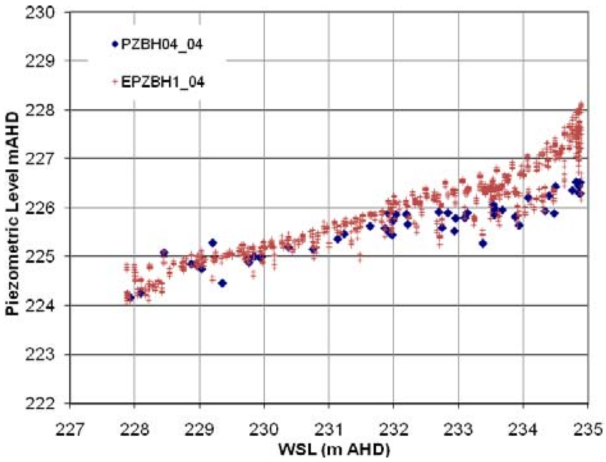

Figure 1 Piezometers at left abutment

Figure1 shows that the pore water pressures in the left abutment further increase at water levels above approximately 234.2 m AHD. This increase may be related to the installation of the clay liner in the vicinity of the existing spillway and the flux of ground water from the left hillside above the dam abutment.

Based on the water chemistry test results and the piezometer readings, the pressurised Lsm zone most likely carries water from both the dam abutments and the reservoir. A trend of reducing pore water pressure readings while maintaining high correlation to the reservoir level (r^2 = 0.9 at the downstream toe) with increasing distance from the reservoir indicates that the Lsm zone forms a semi-confined aquifer (Figure 2).

These high correlation coefficients indicate very permeable dam foundations, which is consistent with the insitu rising head permeability testing. The ranges of the estimated permeability coefficients of the Lsm and Las zones are $1.5x10^{-6}$ to $7.0x10^{-6}$ m/s and 2.7 $x10^{-7}$ to $2.9x10^{-7}$ m/s, respectively.

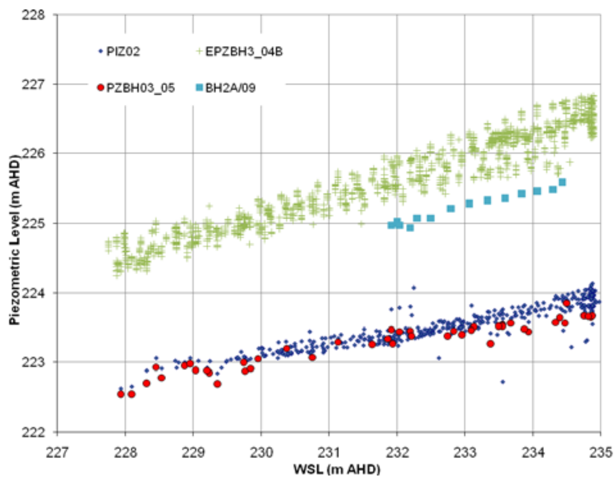

Figure 2 Piezometer reading in Lsm

The installation of the pore water relief wells in 1962 has had only limited effect on the pore water pressures in the Lsm zone. This is demonstrated by the high correlation and linear regression coefficients between the piezometric levels in the Lsm zone downstream of the dam and the reservoir levels.

The pore water pressure line estimated from the piezometer readings is presented in Figure 11.

Engineering properties of foundation soils

As a result of the long-term leaching and re-deposition of minerals under changing groundwater levels, the lateritic soils at Millstream Dam contain large (sand size) clay aggregates that have built up over time. A key difference between each of the lithological layers described above is the nature of the clay and clay aggregates, and the porosity between these aggregates (Herza et al 2010). The clay aggregates are held together and bonded to each other by iron sequioxides, the degree of cementation varying from layer to layer. The presence and configuration of the clay aggregates was investigated by electron microscopy. The EM images demonstrate that a porous matrix has developed mostly in the zones Lapl (Figure 3), Lsm (Figure 4) and Lal (Figure 5).

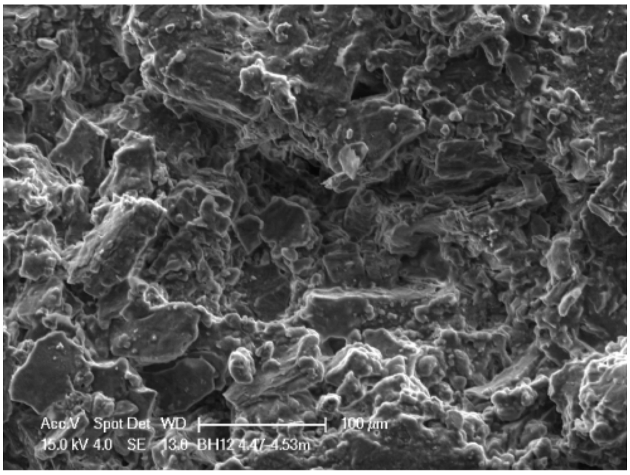

Figure 3 Electron microscope image of Lapl

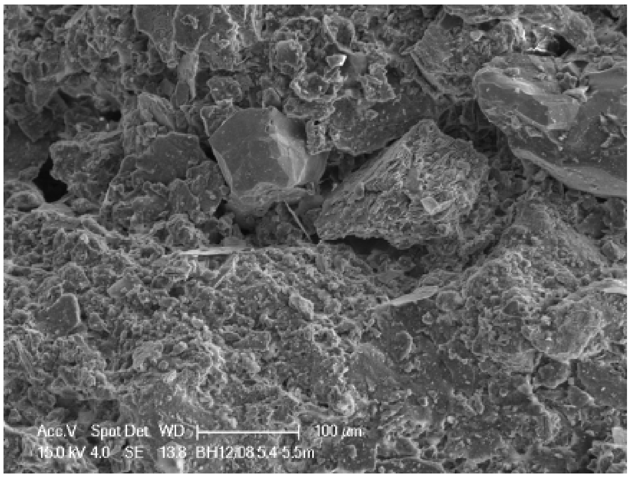

Figure 4 Electron microscope image of Lsm

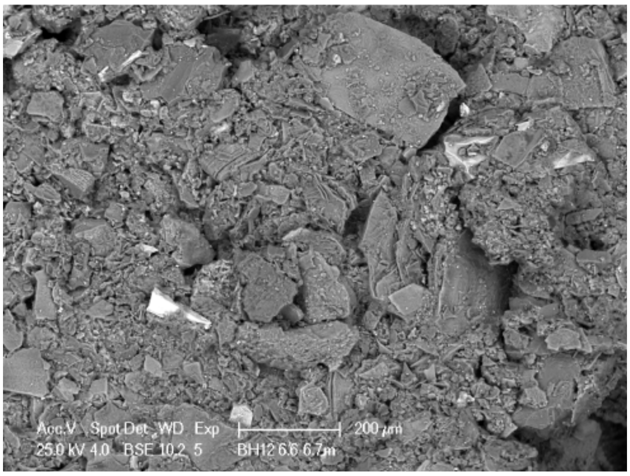

Figure 5 Electron Microscope Image of Lal

This intra- and inter-aggregate bonding has a significant impact on the engineering properties of the affected zones, which is further discussed below.

A number of geotechnical investigation programs have been carried out at the Millstream Dam site, including the original design and construction between 1956 and1961, the upstream blanket installation in 1988 and the recent proposed embankment raising (2004-2005 and 2007-2009). These investigations included the drilling of more than fifty boreholes, recovery of undisturbed samples for extensive laboratory testing, ground water sampling and laboratory analyses. To determine the profile of the bedrock, geophysical tests (ground magnetic, seismic refraction and electrical resistivity) were also included in the investigation program.

The latest geotechnical investigations were focused on the engineering properties of the Lapl and Lal layers affected by the Lsm zone. The Lapl material, although having grading characteristics similar to the overlaying upper pallid zone (59% to 80% of fines – particles < 75ηm), has comparatively lower clay content (1% to 44%), higher moisture content (33.3% to 63.2%) and lower dry density (0.99 t/m^3 to 1.32 t/m^3). The Lapl material can thus be considered as the pallid zone material in its softened state at the contact with the pressurised aquifer. As such it exhibits comparatively low shear strengths.

The Lsm materials are generally coarser than the materials encountered in the overlaying and underlying zones. The fines content in Lsm ranges between 13% and 35%, dry density varies from 1.07 t/m^3 to 1.46 t/m^3 and average moisture content is 24.5%.

The grading of Lal (fines content between 36% and 63%) is generally finer than the overlaying Lsm and underlying saprolite zones, but coarser than the Lapl materials. Despite its relatively low dry density, around 1.20 t/m^3, and high moisture content (32.6% - 58.5%) the Lal material was found to be in generally competent with only slightly lower strength that the much denser saprolite of dry density 1.41 t/m^3.

Similarly to the saprolite, the Lal zone containsrelicts of the parental rock and can be considered as the upper part of the saprolite zone modified at the contact with the pressurised Lsm horizon.

Although some of the materials encountered in the Lapl, Lal and mainly in the Lsm zone have sandy appearance, the electronic microscope imaginary (Figure 6) revealed that the coarser aggregates are formed by uniformly oriented clay platelets bonded into stiff masses These are also bonded together and to other minerals, forming a high porosity, high void ratio, low dry density matrix. This gives this material high permeability for a clay and as such traditional correlation of the permeability to particle sizes such as Hazen formula would be invalid.

With mechanical working, the inter-aggregate bonds will gradually break down and the platelets will re-position themselves. Further working will sever the intra-aggregate bonds and the platelets will disintegrate into a clay suspension.

Due to this micro-mechanical structure, the materials can exhibit both the behaviours of granular and cohesive soils depending on the degree of mechanical working (loading, spreading, compaction) applied.

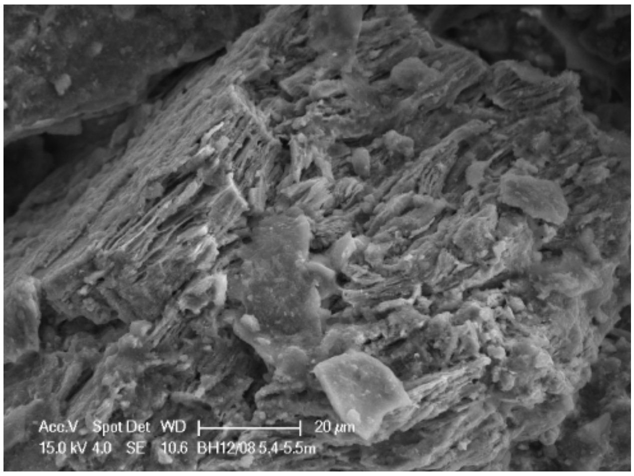

Figure 6 Clay Aggregate in Lsm

In addition to the clay platelets, the electron microscope images of the Lal material derived from dolerite bedrock revealed uncharacteristic interconnecting fibrous minerals (Figure 7). Despite their resemblance to tubular halloysite, the mineralogy of these fibrous minerals was not established.

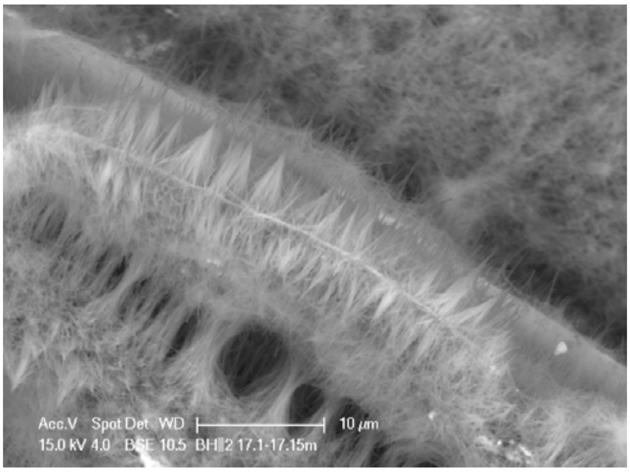

Figure 7 Fibrous minerals in Lal zone above dolerite bedrock

The sample of Lal, in which the fibrous minerals were identified, exhibited pronounced expansive behaviour (up to 40% on sample recovery), which was not observed on any other in-situ material. Given that dolerite is not present under the footprint of the existing or the raised dam, the significance of the expansive soils in one Lal sample could be seen as minimal. However, it demonstrated that the characteristics of laterite soils are related to the parental rock type and the selection of the representative samples is important.

Foundation strength characteristics

To determine the shear resistance of the foundation soils at Millstream Dam, a number of triaxial and consolidation tests were carried out on undisturbed samples of Lapl, Lsm and Lal in years 1988, 2004/2005, 2008 and 2009.

The triaxial test results displayed a variety of soil behaviours, which are attributed to the micro-structure of the foundation soils described previously. The results also displayed high sensitivity to the testing procedures (Herza et al, 2010). Despite this variability and sensitivity, the triaxial results plots (mean effective stresses ‘p’ versus the deviatoric stresses ‘q’) allowed the development of a common failure envelope for the test results in a given lithological unit. The lower failure envelope was then used to estimate the effective friction angles, as shown in Figure 8 below.

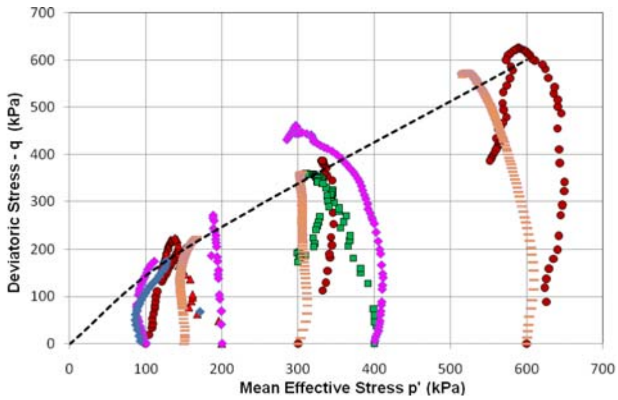

Figure 8 Lapl p' - q plot

The estimated friction angles displayed no correlation to the plasticity index or fines content of the tested samples (Figure 9 and Figure 10). This demonstrates that published correlations between plasticity index and effective friction angle (e.g. Kenney 1959; Terzaghi et al 1996) should only be used with site-specific data confirming its applicability, especially for laterite soils.

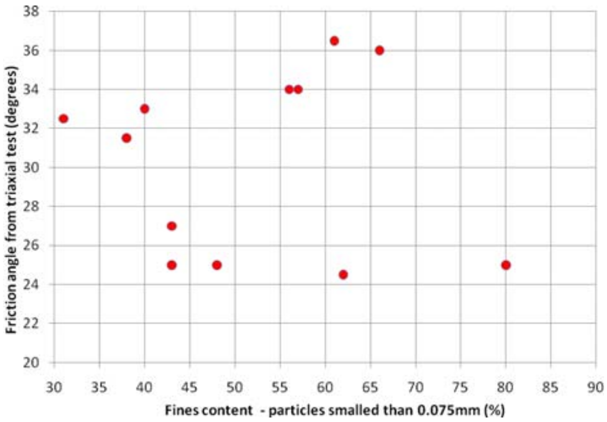

Figure 9 Fines content versus friction angle

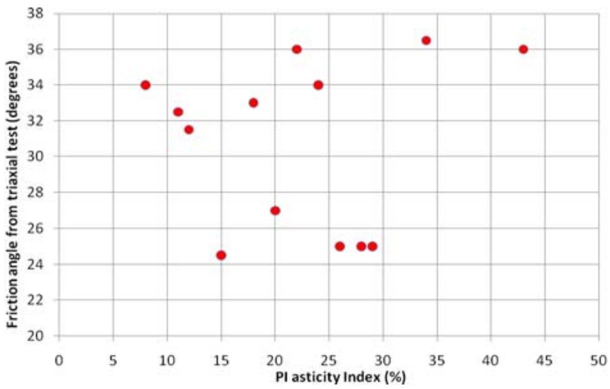

Figure 10 Plasticity index versus friction angle

Foundation treatment

The major issues associated with the foundation soils at Millstream Dam, discussed in the previous paragraphs are:

- a pressurised aquifer formed in the laterally continuous semi-horizontal Lsm layer under the centre of the dam and its lower left abutment;

- softened and comparatively low strength pallid zone materials (Lapl) overlaying the Lsm zone, which exhibit rapid loss of undrained shear strength with increasing displacement (stain softening); and
- softened saprolite materials (Lal) underlying the Lsm zone.

From an engineering perspective, the relatively high permeability of the Lsm layer under the dam presents the following potential issues:

- pressurised foundations resulting in low effective stress unless this layer is drained with potential for dam instability;
- uncontrolled water release from the Lsm layer (without a filter) could lead to a piping incident;
- instability of the dam during and after raising, and during and after seismic event; and.
- difficulty in maintaining stability during foundation excavation.

To mitigate the risk represented by the Lsm layer, several foundation treatment options were considered. These included: installation of positive upstream and/or downstream cut-offs; pressure relief wells; and effective draining of the Lsm zone.

Assessments of the dam stability during and after construction using different foundation designs were undertaken, using both limit equilibrium and finite element models (Vitharana and Terzaghi, 2005).

Construction of the upstream cut-off was selected as the most desirable solution from an engineering perspective. However it was considered that the dam safety risks could be mitigated by controlled discharge of seepage from the foundation strata, at a significantly lower cost. On this basis and on consideration of the relatively low volume of seepage water expected to be discharged, the option of an upstream cut-off was not selected.

The selected foundation treatment comprised excavation of the relatively shallow Lsm material underneath the centre and lower right abutment and replacement with free-draining filter media. In addition, a cut-off trench will extend into the right abutment to intersect and drain the entire width of the Lsm zone. This solution was preferred to the installation of pressure relief wells for the following reasons:

- the exposed foundation strata can be inspected during the construction;
- the pressure relief well screens could get blocked by iron oxide minerals and bacteria;
- unlike the pressure relief wells, the foundation cut-off extension will ensure that the entire width of the Lsm zone is intersected;
- there is risk that the pressure relief wells would only reduce the pore water pressures locally, as the Lsm material is not homogeneous and lenses of more and less permeable material exist in the layer; and
- the supposedly positive effect of the pressure relief wells installed in 1962 was not confirmed.

The soft materials under the right abutment are not to be replaced (due to the thickness of the overlaying strata). Therefore, the foundation loading during construction will be controlled by fill placement, and the pore water dissipation especially in the lower pallid zone will be monitored. Numerical analyses showed that if these layers are strained beyond their peak stresses during the construction, it is highly likely that they would collapse under an earthquake in the future. Therefore, it is imperative that the fill placements be controlled in such a manner that the concurrent dissipation of construction-induced pore pressures is allowed to take place.

A section through the raised embankment showing the foundation replacement is presented in Figure 12.

Conclusions

The geotechnical investigations and the laboratory test results at Millstream Dam demonstrated that the engineering characteristics of laterite profiles are related to the parental rock material and the environment, in which the profiles were formed.

Secondary erosion and leaching have significantly modified the original constitution of the laterite soils and a porous intra- and inter-bended matrix was formed.

The highly structured soils at Millstream Dam exhibited behaviours of both granular and cohesive soils, depending on the degree of clay particle aggregation and iron oxide cementation. Comparison of Plasticity Index and triaxial test results demonstrated that no correlation between the PI and the estimated friction angle exists in the foundation soils at Millstream Dam.

Considering the unusual nature of the foundation soils, particularly Lsm layer, it was decided to remove these wherever possible and also to control the rate of fill placement. To mitigate the risk of piping underneath the embankment and to improve the dam stability, it is proposed that the high permeability layer in the dam foundation profile should be drained by replacing the entire laterite profile above bedrock at the centre and lower right abutment.

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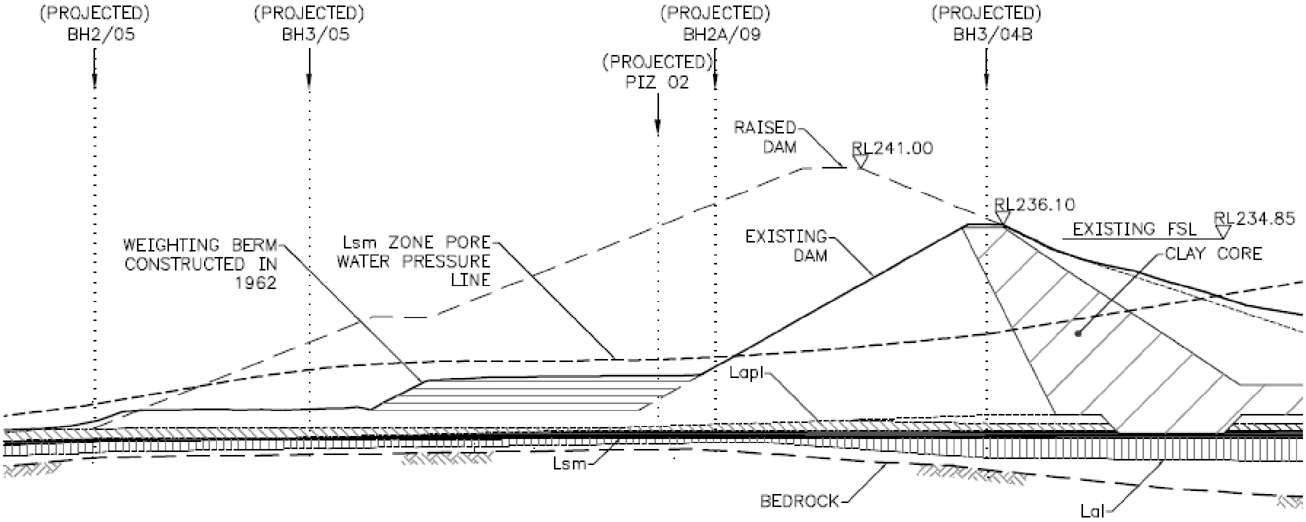

Figure 11 Schematic cross section of existing Millstream Dam

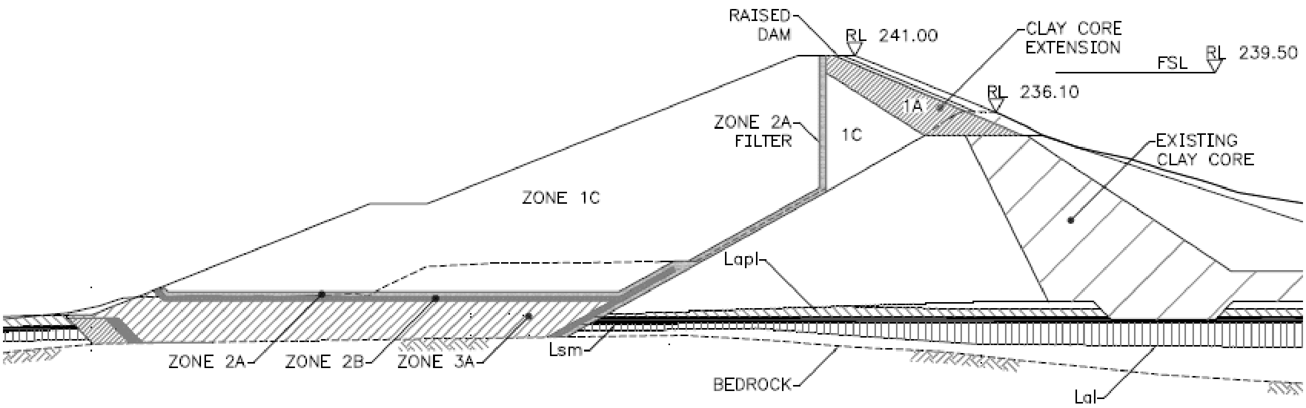

Figure 12 Schematic cross section of raised Millstream Dam