

The Design and Construction of Kargu Dam

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SYNOPSIS. Kargu Reservoir is located within the Andulau Forest Reserve in Brunei Darussalam and was constructed to regulate low flows in the Sg¹ Belait. Raw water is abstracted from Sg Belait for domestic and industrial supply and a high level of reliability under drought conditions is required. The reservoir has a gross storage volume of 14.3Mm³ and will be used to increase Sg Belait yield by 110MI/day for downstream abstractions at the 1 in 100 year low flow event.

The earthfill embankment dam is 27m high above foundation level and 440m long at crest level, incorporating 1.2Mm³ earthfill. The valley floor comprised thick peat / soft alluvial clay overlying silty-fine alluvial sand and weak sandstone, with colluvium covering the hill slopes. The main focus of the ground investigation was on the valley floor alluvium and liquefaction potential under seismic loading. A comprehensive ground investigation was carried out and various sampling and testing methods were carried out to characterise the nature of the alluvium for stability and liquefaction assessment.

A key aspect of the design of the dam was the removal of large quantities of peat and soft alluvial clays present over the valley floor at depths of up to 12m below ground level. A deep well dewatering scheme was installed comprising 105 deep wells each sunk to 30m depth, with airlift pumps used to draw down groundwater levels and facilitate excavation and filling operations.

The waterproof element of the dam was formed by a central rolled clay core and long upstream clay blanket. The clay core material was processed mainly from weathered and fresh mudstone requiring significant conditioning to produce a satisfactory cohesive fill.

This paper describes the field investigation, design aspects and construction of the dam and performance during first filling of the reservoir.

BACKGROUND

The water supply infrastructure in Brunei is based around separate supply zones for each of the four districts, which are broadly divided according to the main river basins. The Belait District is the largest of the four districts and has a catchment of 1,872km² upstream of the river abstraction pumping stations at Badas. The water

¹ Sg: Sungai - river or stream

DAMS: ENGINEERING IN A SOCIAL & ENVIRONMENTAL CONTEXT

supply system is currently supplied by direct river abstraction at Badas coupled with a river barrage to counteract saline intrusion at times of low flow. Domestic demand is expected to increase in the future and the country's main industrial users (oil and gas industries) are also located in the district and require an assured water supply.

MWH was commissioned to carry out desk studies, field reconnaissance and environmental impact assessment for the scheme in 1995 but the scheme was subsequently put on hold in 1997 due to the Asian financial crisis. Work on the scheme resumed in 2003, with topographical surveys and field investigation followed by preliminary and detailed design. A construction contract was awarded to TSL Construction Sdn Bhd in October 2007 with completion by end of 2011.

PROJECT DESCRIPTION

Kargu Reservoir has a gross storage volume of over 14.3Mm³ and covers a surface area of 240ha at its Full Supply Level (FSL) of 29.0m BSD. The 440m long earthfill embankment dam stands 27m above the lowest foundation level and has upstream slope of 1 on 4 and downstream slope of 1 on 3. Both upstream and downstream faces have intermediate berms - the upstream berm incorporates the main cofferdam and the downstream face incorporates a narrow berm to facilitate surface water drainage. Access to the site was via a new 7km access road also constructed as part of the project.

A 3.5m 'D' shaped reinforced concrete diversion / draw-off culvert is located at the toe of the left abutment and incorporates a 7m internal diameter free standing draw-off shaft / tower within the upstream shoulder of the dam. The diversion culvert was converted to house the 1.2m diameter steel draw-off pipework upon diversion closure and reservoir impounding. Energy dissipation for the outlet works is achieved using a pair of tapered 1,000mm /800mm submerged discharge valves within the outlet structure.

The spillway is remote from the embankment, some 300m to the left and comprises a 35m wide ogee shaped mass concrete weir leading directly to a spillway chute and USBR Type III stilling basin and reno-mattress lined tailrace channel. The routed design outflow of 320m³/s was derived for the Probable Maximum Flood (PMF) event and the final design was verified by a physical hydraulic model (BHR, UK) with particular attention to the performance of the energy dissipation structure and tailrace channel under different tailwater levels. The tailrace channel re-joins the outlet channel downstream of the dam.

A diffused bubble plume de-stratification system was also installed in the reservoir to reduce the effects of temperature stratification of the reservoir.

The general arrangement of the dam and ancillary works is shown on Figure 1.

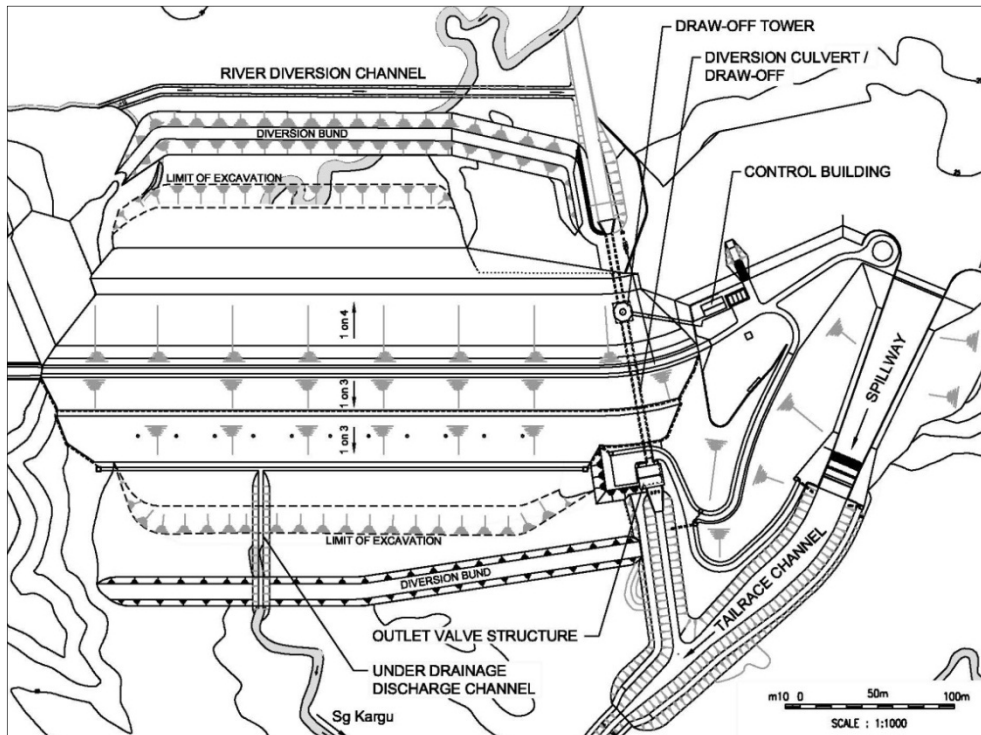


Figure 1. General Arrangement

HYDROLOGY AND CATCHMENT

The dam site is located on the upper reaches of the Sg Kargu, which is a tributary of the much larger Sg Belait. The catchment area of Kargu Reservoir is 14.3km² and is covered by thick, uninhabited secondary rainforest. The valley is characterised by a relatively wide alluvial floodplain trending northeast-southwest with gentle strike ridges forming the watershed. The Mean Annual Average Rainfall is 2,660mm.

The hydrological investigations centred on two possible modes of operation for the reservoir:

- i) a 'direct supply' scheme, whereby the reservoir would transfer raw water directly to a water treatment plant and to supply,
- ii) a 'river regulation' scheme, whereby the reservoir would make strategic releases to the main river system (the Sg Kargu to Sg Belait) to supplement natural flows during periods of low flow or drought. Water being abstracted at Badas, treated and put into supply.

The studies showed that the river regulation scheme would provide greater yield to the water supply system (even allowing for losses in the river system), as only strategic releases from the reservoir would be required to augment low flows in the Sg Belait. The scheme is designed to utilise the upper zone of the reservoir storage to reduce the impact of thermal stratification, which is a common problem with reservoirs in tropical climates. With a working storage of 7Mm³, the system yield is expected to increase from 150MI/day to 263MI/day at a 1 in 100 year level of reliability.

DAMS: ENGINEERING IN A SOCIAL & ENVIRONMENTAL CONTEXT

GEOLOGY AND FIELD INVESTIGATIONS

The reservoir site lies near the northern edge of a broad 2,300km² synclinal basin (the Belait Syncline) of Miocene-Pliocene (sedimentary) rocks, which underlies the catchment of the Sg Belait and Sg Tutong. The dam site lies close to the junction between the older Seria Formation and the younger Liang Formation. The predominant rock types are weak and very weak fine-grained sandstones and dense sands interbedded with weak and very weak silty mudstones and stiff clays of the Liang Formation.

At the dam site, the abutments are formed by a pronounced strike ridge formed by a thick mudstone/clay bed. The underlying and overlying weak sandstones/sands have been eroded to form irregular tributary valleys and embayments off the main valley (see Figure 2). The Sg. Kargu floodplain varies in width at the dam site from about 180m, where the mudstone strike ridge forms a slight constriction at the upstream part, to around 350m in the downstream part.

The valley floor is occupied by alluvial deposits which vary in composition according to their depth, fine sands in the lower part of the buried valley channel passing upwards into very soft clayey deposits and poorly humified peats nearer the surface. The proto-Kargu valley floor is buried beneath a maximum thickness of about 25m of alluvium, which accumulated as a consequence of the post-glacial rise in sea level.

Field investigations comprised topographical surveys of the dam site, catchment boundary and main river channels and ground investigation at the dam site and along the access road route. The ground investigation contract was awarded to a local specialist contractor (Teca Sdn Bhd) in 2005 under the supervision of MWH. The ground investigation was carried out under difficult conditions, in a remote tropical jungle with logistics difficulties and difficult working conditions. The investigation techniques included boreholes, trial trenches/pits, wash probing, CPTs, undisturbed 'Mostap' sampling, Mackintosh probing and geophysical traverses.

The main focus of the investigation was to characterise the thickness and nature of the valley floor alluvium, as this had the greatest impact on the feasibility and design of the dam. The sequence of superficial deposits and bedrock is summarised as follows:

- Upper Alluvium: Silts and very organic clays and peat, consisting largely of organic material including timber. The predominant member near the surface is peat, interbedded with very soft and soft clay and loose sand layers. The upper alluvium varied in depth across the valley with a maximum thickness of 12m.
- Lower Alluvium: Pale grey silty fine sand, loose to medium dense. The thickness of the alluvial sand was approximately 15m in the centre of the valley.
- Colluvium: Slope-wash soils (colluvium) which are highly weathered, strongly leached tropical red and yellow silty sandy clays and silty sands. They grade downwards into completely weathered bedrock and have a variable thickness up to about 1.5m.

Bedrock: Very weak, uncemented sandstone of the Liang Formation, inter-bedded with weak mudstone/stiff clay.

The abutment ridges comprised an upstream dipping (apparent dip of 8°-10° upstream) mudstone/siltstone/clay unit with weak sandstone above and below. The mudstone was about 15m thick in both abutments with unconfined compressive strength ranging between 77kPa and 2MPa (i.e. firm clay to weak rock). The natural moisture content of the mudstone varied between about 31% in its upper weathered parts immediately below the Alluvium and Colluvium to values of about 3% to 6% in the deeper fresh weak rock. Bulk densities lied in the range 1.80 - 2.39 Mg/m³ and dry densities in the range 1.38 - 2.09 Mg/m³. Index properties of weathered mudstone comprised mostly clays of low to intermediate plasticity. The permeability of the mudstone determined by variable head tests in the piezometers varied between 1.1 x 10⁻⁸ m/s and 1.5 x 10⁻⁸ m/s, averaging 1.2 x 10⁻⁸ m/s (i.e. about 0.1 Lugeons).

The sandstone beds were weathered below the Alluvium and Colluvium to the consistency of a dense and very dense sand soil. Core recovery was generally not possible, although UCS values on two specimens of weathered sandstone gave 168-265 kN/m² (i.e. weak). The permeability of the sandstones determined by variable head tests in the piezometers varied between 6.1 x 10⁻⁸ m/s and 2.6 x 10⁻⁶ m/s average 1.1 x 10⁻⁶ m/s (i.e. about 11 Lugeons).

In order to obtain relatively “undisturbed” samples of the alluvial sands (essentially in terms of their particle size distributions) for the purposes of liquefaction assessment, continuous sampling using “Mostap” sampling equipment was used from the base of the peats. The equipment comprised a jack-in rig that pushed a 65mm diameter sample tube into the alluvium behind a cone. Samples were recovered within the PVC casing in thin ‘stockings’ and were free from washout of fines. The “Mostap” samples were considered less likely than conventional “disturbed” samples to suffer a loss of their fines content during sampling from below the water table and this was confirmed in practice.

The conventional samples frequently indicated soils with d₅₀ >0.25mm (i.e. fine sands) whereas the “Mostap” samples almost invariably gave values of d₅₀ <0.25mm and often gave values of d₅₀ <0.15mm (i.e. silty fine sands). In situ permeability tests were carried out in 14 No. standpipe piezometer clusters installed in the alluvial sands specifically for permeability testing. These tests gave values ranging from 5.1 x 10⁻⁷ m/s to 5.7 x 10⁻⁶ m/s, averaging 2.1 x 10⁻⁶ m/s.

The ground water level in the upper alluvium across the valley floor was generally at ground level although artesian pressure of up to 4.5m were recorded in the lower alluvium and bedrock in the middle / right side of the valley. Groundwater levels in the abutment ridges were high which was consistent with the presence of artesian pressure in the bedrock beneath the floodplain alluvium and the existence of upward hydraulic gradients in the groundwater and hence general upward (influent) groundwater flow from the bedrock into the alluvium.

A simplified geological plan and section is shown on Figure 2.

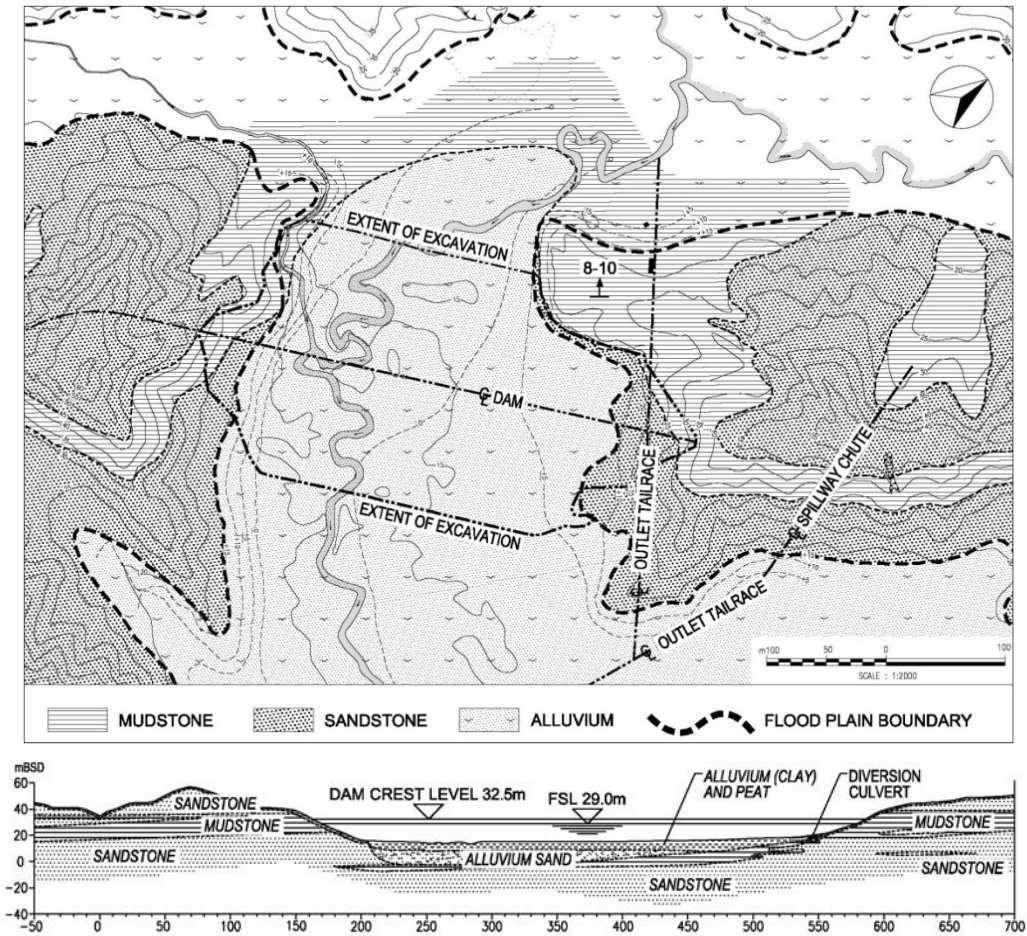


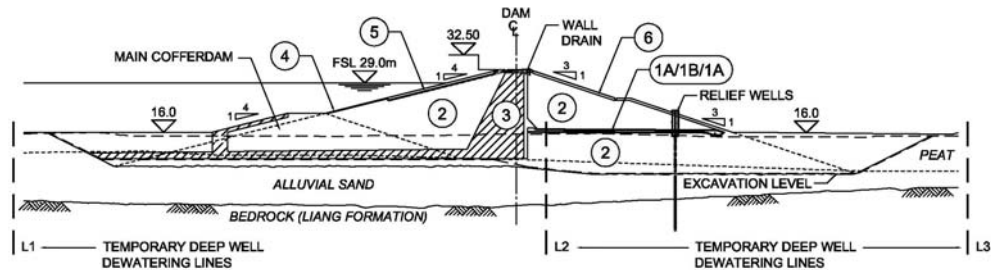
Figure 2. Geological Plan & Section

EMBANKMENT DESIGN

The upper alluvium was highly compressible and very weak. The valley abutments were relatively narrow and a wide, multi berm embankment design was not considered to be feasible. It was therefore decided that all peat, organic and alluvial clay should be removed from the dam footprint and that a conventional zoned embankment dam should be founded on the lower alluvial sand formation. This required excavation of 600,000m³ of unsuitable materials at depths of up to 12m below the water table.

The embankment was zoned to make best use of available materials derived from excavation for the spillway works, diversion works and access roads and incorporated a rolled clay core and upstream clay blanket (some 100 m long), with sandstone fill shoulders. A critical filter wall drain at the downstream side of the core and fine/coarse/fine filter blanket extended over the downstream shoulder and abutments. Upstream slope protection was provided by a combination of rip rap and beaching stone. All rockfill materials were imported from neighbouring Malaysia and graded granular filters were screened and graded in river abstraction quarries located in the Temburong District. A series of 12 No. wedge wire screened relief wells were provided close to the downstream toe to control artesian

pressure in the foundation. A typical cross section through the embankment dam is shown on Figure 3.



- | | | |
|------------------------------|------------------|------------------------------|
| (1A/1B) Fine / Coarse filter | (2) General fill | (3) Core / blanket |
| (4) Beaching stone | (5) Rip rap | (6) Colluvial fill / topsoil |

Figure 3. Typical Embankment Cross Section

The initial design concept was to strip colluvium from the hill slopes within the reservoir basin to produce a cohesive fill for the core and supplement this by processed mudstone from bulk excavations. The thickness of the colluvium varied but was generally less than 1.5m and therefore difficult to win and work efficiently.

Following initial clearance works, it became apparent that the quantity and quality of the colluvium would be insufficient and the fall back option of processed mudstone was initiated. The advantage of using the mudstone was that the required excavation produced surplus quantity of this material and haulage distances were very short, however conditioning the fresh mudstone was difficult in the climatic conditions and given the plant available to the contractor.

Embankment Stability

The embankment was founded on silty fine alluvial sand. This material was generally very consistent over the entire area of the foundation excavation. The ground investigation had revealed that these sands were loose in places (SPT $N < 4$), although it is suspected that the sub-artesian groundwater pressures loosened the base of the boreholes during the tests, thus affecting the validity of the results. CPT tests were carried out, but again there were practical difficulties in using small screw-in type jack-up rigs in the peat that meant that driving depths were generally less than 10m (i.e. little penetration into the lower alluvium).

General fill (ex. sandstone) was readily excavated to produce a silty sand fill that was placed at natural moisture content. The core and upstream clay blanket material was mainly derived from weathered and fresh mudstone. This material broke down during handling but needed to be ripped and conditioned to produce a homogeneous clay fill. Index testing for this material gave an average of $LL=29\%$, $PL=18\%$ and $PI=11$ (i.e. a low plasticity clay). Natural moisture content was in the range 3% to 6% for fresh material at depth and required significant adjustment in moisture content to bring the material within its plastic range, with an average placement moisture content of 22%.

Bedrock over the main valley was generally sandstone, thinly bedded with mudstone. The main mudstone unit dipped across each abutment and required

DAMS: ENGINEERING IN A SOCIAL & ENVIRONMENTAL CONTEXT

some local blanketing to close any short leakage paths through the more permeable sandstone.

Limit equilibrium stability analysis using effective stress parameters was carried out to determine the embankment geometry for static and seismic stability. The effective stress design parameters used for stability analysis are summarised in Table 1, below.

Table 1. Material Properties

Material	ϕ' (deg)	c' (kPa)	γ' (kN/m ³)	k (m/s)
Alluvial sand	30	0	19	2×10^{-6}
Sandstone fill	30	0	19	2×10^{-6}
Core material	27	0	20	1×10^{-8}
Bedrock (sandstone)	42	0	21	2×10^{-6}

Excess pore pressures during construction were expected to be minimal due to the permeable nature of the sandstone fill and short drainage paths for the core zone, although conservative assumptions were adopted in the analysis for the end of construction case. Embankment slopes of 1 on 3 (downstream) and 1 on 4 (upstream) provided satisfactory factors of safety under all loading conditions with some margin in reserve for any unexpected variation in the alluvium.

Seepage Control

The foundation geology did not lend itself for a full cut-off in to impermeable bedrock below the dam. The upstream dipping mudstone unit extended beneath the valley alluvium, although the proven extent of this unit extended well into the reservoir basin and would have required a deep and expensive cut off to be effective. Instead, as the foundation excavation needed to be relatively deep to remove the unsuitable materials, an upstream clay blanket was adopted to control under seepage beneath the main part of the embankment. The clay blanket was connected to the mudstone outcrop adjacent to the inlet culvert and local blanketing of the abutments was carried out to close seepage paths. The length of the upstream blanket was approximately 100m and was placed at a level some 10m below final ground level. The blanket thickness varied from 2.5m thick at the core to 1.5m thick at the upstream toe. A filtered drainage blanket was also placed beneath the downstream shoulder and abutments, together with relief wells to control artesian pressures in the foundation bedrock.

Empirical guides for design of upstream blankets suggest that a length of approximately 10 times the driving head should reduce under seepage to tolerable levels. In the case of Kargu Dam, a length/head ratio of 8.1 was provided across the blanket and 12.3 from upstream toe to downstream toe. A 2D finite element seepage analysis was carried out to assess the likely seepage quantities, pore pressures and seepage gradients. These studies indicated that seepage quantities could be up to 200m³/day to 400m³/day over the full width of the dam, which was deemed to be acceptable. A reduction in seepage of only 10 % was estimated if the upstream blanket was fully connected to the underlying mudstone strata within the

reservoir basin and therefore, it was decided that this would entail significant additional cost but limited benefit.

Liquefaction Assessment

Liquefaction is the build-up of pore pressures in soils during seismic shaking, resulting in strength loss and deformation of the soil. Liquefaction generally affects cohesionless soils, which are in a loose state. The embankment fill itself was densely compacted, which takes it outside the range of materials considered to be particularly vulnerable to liquefaction. However, the foundation of the embankment comprises some loose silty sands and the potential for liquefaction of this material was examined.

Estimates of Peak Ground Acceleration (PGA) by MWH for other nearby dams in Brunei suggested a value of about 0.05g would be appropriate for seismic design. An assessment of the liquefaction potential of the alluvium was made using the empirical approach advocated by Seed & De-Alba for the pre-existing situation and Seed & Harder for the post embankment condition. These methods use soil density (SPT N), grading (fines content) and seismic acceleration to estimate the potential for liquefaction, which can be expressed as a factor of safety.

The 'Mostap' samples were particularly useful for confirmation of the actual particle size distribution of the soils and fines content. Calculations indicated that there should be a reduction in the liquefaction potential post embankment construction, especially beneath the central part of the dam because of the increased effective stress. The effect diminishes towards the embankment toes as the thickness of fill decreases. However, the factor of safety against soil liquefaction was estimated to be in excess of 1.6 at the toe when subjected to a PGA of 0.1g.

Deep Well Dewatering System

A deep well dewatering system was designed and installed by a specialist dewatering company, International Groundwater Technology (Singapore). The scheme included three lines of dewatering wells across the valley: along the upstream toe, downstream toe and just downstream of the core zone. Each well was sunk to 30m depth and were spaced at 10 m centres.

The wells incorporated 100mm diameter slotted PVC screen, surrounded in graded gravel pack and incorporated air-lift pumps connected to a common manifold discharge pipe. The system was operated from a series of air compressors and ran continuously throughout the foundation excavation and filling works. This system was supplemented by three large surface pumps set on floating pontoons to discharge surface run-off into the excavation. The foundation excavation was approximately 350m x 220m and up to 12m deep.

Pumping tests in the wells showed that the bulk permeability of the alluvium/sandstone bedrock ranged between 2×10^{-5} m/s to 8×10^{-6} m/s and consequently, the system was able to drawdown the ground water level relatively quickly. The efficiency of the wells reduced over time and some loss of fine material was observed by surface depressions around the well heads. All wells

DAMS: ENGINEERING IN A SOCIAL & ENVIRONMENTAL CONTEXT

were grouted following decommissioning of the system. The system is illustrated in Figure 3.

Compressed air was forced through the nozzle at the base of the pump-head, which forced water in the riser pipe to the surface and into a common discharge pipeline.

Earthworks control

All unsuitable peat and alluvial clays were excavated from the dam footprint and disposed by end tipping into an adjacent valley, with earth bunds formed to control the peat slides.

The initial excavation was very messy, although once water had drained and was pumped out of the pit then in many instances the peat could be excavated from a face with vigilant operators ready to back up at the first sign of peat sliding into the excavation! The dewatering system was effective in reducing ground water levels in the alluvium, although the final excavation at the lowest part of the valley proved difficult to manage. In order to remove the final low-lying unsuitable material, it was decided to employ the 'displaced filling' technique, whereby sand fill was dumped at the leading edge of a fill platform and dozed out over the waterlogged area. This provided a stable platform for the plant to run on and displaced the wet slurry material so that it could be removed. The leading edge was advanced until the entire area was stable. Trial pits excavated through this platform confirmed that all the unsuitable material had been removed and density tests confirmed that the sand was suitably dense.

The clay core and upstream blanket was placed wet of optimum moisture content and compacted to a shear strength specification. Average shear strength measured during placement was 77kPa (hand vane) and 86kPa (UU triaxial), which was within the specified range of 60-100kPa. The mudstone fill required extensive conditioning to break down hard clay lumps and raise the moisture content to within the plastic range. The fill conditioning included watering and ripping (using various methods) to breakdown the clay fragments to produce a homogeneous clay mass with a uniform moisture/clay matrix. Compaction was achieved by a combination of 4 No. passes of a CAT 815 (15T dead weight sheepsfoot compactor with extended pads welded on the feet) and 4 No. passes of a 10T vibrating padfoot roller.

The low plasticity clay was extremely moisture sensitive and quickly lost strength after a heavy downpour and quickly dried out in the baking sunshine. Therefore, the working area was limited to very small areas (typically 20m x 20m), which were immediately covered over with mudstone fill before moving to the next section of the core. Production was very slow and required continuous supervision to ensure that the core material was always kept in acceptable condition.

Hand shear vane testing was the routine measure of acceptability, along with in situ density. Cores were cut in the completed fill for UU triaxial testing, although the limitations of local laboratories led to a wide range of results. Given the difficulties in placing and conditioning the core material, a series of 3 No. cable percussion boreholes were sunk through the completed core with continuous U100 sampling and strength testing to verify the moisture content / strength and homogeneity of the material.

The critical fine filter material was processed from river gravel deposits from the Sg Temburong and transported to site (over a distance of about 100km). The grading of filter was specified following the procedures advocated by Sherrard & Dunnigan for a Category 2 base soil ($0.1\text{mm} < D_{15} < 0.7\text{mm}$ and $< 5\%$ non-plastic fines). Various blended trials were carried out by the contractor prior to acceptance of a compliant material with an average D_{15} size placed of 0.17mm and uniformity coefficient of 9.

Instrumentation

The dam was instrumented on two principal sections. An array of 36 vibrating wire piezometers were installed within the foundation, clay core and blanket and downstream shoulder with all leads taken back to the Control Building. Movement and settlement within the embankment was monitored by a series of 7 No. combined inclinometer / extensometers and the base drainage blanket was divided into three sections with v-notch chambers on the outlets to each. The outlets to all relief wells were also individually monitored by v-notch weir chambers.

The instrumentation recorded a maximum settlement at the end of construction of 480mm in the core zone, 126mm in the alluvial sand under the dam axis and 140mm in the general fill at the downstream berm. Lateral movement was estimated to be less than 120mm. The total settlement was within the range expected with the majority of the settlement occurring within the alluvial sand and core zone.

DIVERSION CLOSURE

Diversion closure was achieved by lowering a *Bi-Steel* gate (Tata, UK) through a pre-formed slot in the culvert, just upstream of the draw-off tower. The gate had a circular opening pre-formed with bolted connections that quickly enabled the lower 1,200mm diameter bottom outlet pipe and bellmouth to be connected. The inside of the steel panel was then in-filled with Grade 40 concrete. The first stage gate was installed within a period of three hours, which then enabled a permanent second stage concrete plug to be formed immediately downstream. The diversion closure arrangement proved very effective and was quick to install. The details of the diversion gate and closure arrangements are shown on Figure 5.

PERFORMANCE DURING FIRST FILLING

The performance of the embankment dam and appurtenant structures during first filling of the reservoir has been within design expectations. The seepage control works are principally monitored by piezometers within the fill and foundation and seepage flow monitoring of the base drainage blanket and relief wells. The pore-water pressures within the lower alluvium and bedrock correlate closely with the finite element model predictions.

The downstream base drainage blanket is effective at controlling pore pressures within the downstream shoulder and seepage quantities from the base drainage blanket are less than $10\text{m}^3/\text{day}$. Flows measured from the relief wells are greater and appear to show an increasing trend with reservoir level, although flows measured before the onset of first filling ranged between $60\text{m}^3/\text{day}$ and $180\text{m}^3/\text{day}$ (Figure 6).

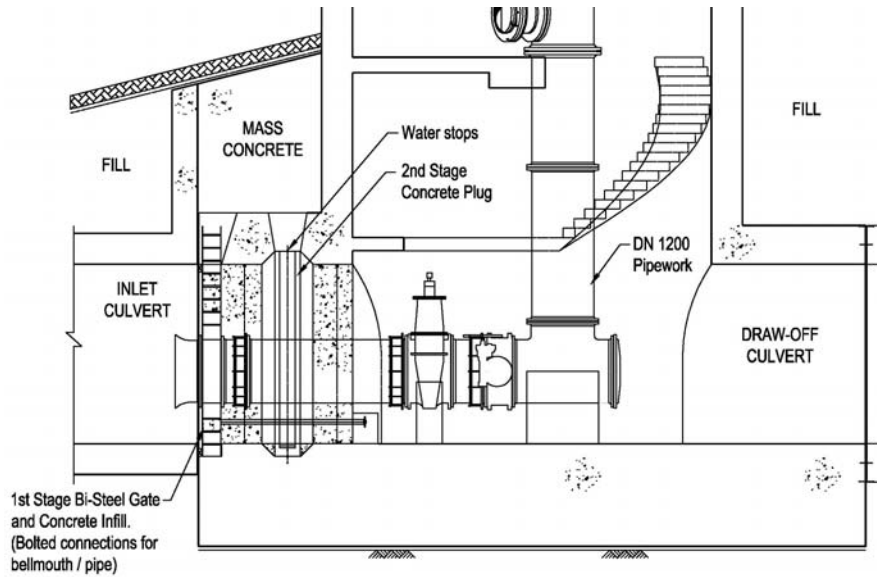


Figure 5. Details of Diversion Plug

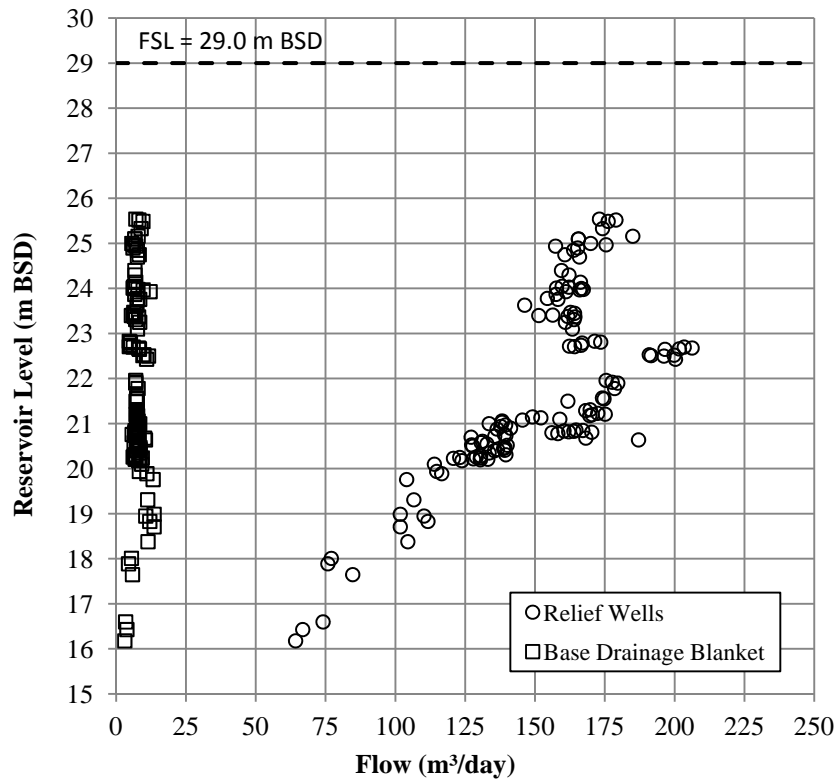


Figure 6. Seepage Flows

The foundation piezometers confirm that the upstream clay blanket is effective at reducing the hydraulic gradient through the alluvium and groundwater levels in the downstream shoulder are below the level of the base drainage blanket.

The performance of the dam continues to be monitored to establish baseline trends although the indications during first filling suggest that the dam is performing as expected.



Figure 7. Photograph of Completed Embankment.

SUMMARY

Kargu Dam is founded on a alluvial silty sand foundation and incorporates a long upstream clay blanket to control under seepage. The following points are noteworthy:

- i) The embankment required significant foundation preparation works, including removal of 600,000m³ of peat and alluvial clays at depths of up to 12m below ground level. A temporary deep well de-watering system comprising 105 well points was effective in reducing ground water levels during the excavation and refilling works. The success of the de-watering system was critical to success of the project – in the event, these works proved to be easier than had been envisaged at the design stage.
- ii) The use of continuous soil sampling techniques ('Mostap' sampling) using push-in tubes was useful in obtaining undisturbed samples of alluvium for accurate grading and visual examination. The work by Seed & Harder was useful for liquefaction assessment.
- iii) The seepage control works consist of a central clay core and long upstream clay blanket (hydraulic gradient of 8) together with filtered downstream drainage blankets and relief wells. Seepage quantities during first filling were minimal and lower than predicted by finite element seepage analysis.

DAMS: ENGINEERING IN A SOCIAL & ENVIRONMENTAL CONTEXT

- iv) The difficulty in obtaining sufficient colluvium from the hill slopes prompted the use of processed mudstone to form the clay core and upstream blanket. Significant effort was required to condition the fresh mudstone into a homogeneous plastic clay, which led to construction delays. The climatic conditions also hampered placement and compaction of the core and blanket and close supervision was essential to ensure that a satisfactory core free from voids was achieved.
- v) The use of a *Bi-Steel* diversion closure gate as the first stage plug was an effective, quick and cost effective solution to achieve protection from flooding during the diversion closure stage. This approach is currently being used by the authors on other schemes with greater river flows.
- vi) The performance of the dam and appurtenant works during first filling has been satisfactory, especially the seepage control works.

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