Remedial grouting works to two dams in Hong Kong

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SYNOPSIS. Tai Tam Upper and West Col Dams in Hong Kong had experienced substantial leakage over an extended period. Recommendations were made in the interests of safety for both dams to investigate and carry out remedial grouting works to reduce leakage to acceptable levels. Reference is made to their history and earlier unsuccessful attempts to reduce and control leakage.

The paper presents a brief history of the dams and gives details of the investigation and remedial grouting works carried out by the Design and Construction Divisions of Water Supplies Department (WSD), Hong Kong under the direction of the Author as Advisor to WSD. Types of grout and injection techniques to effectively to reduce foundation permeability are described. Reference is made to results of leakage monitoring as the works proceeded and to the results of monitoring since completion of the works. Grouting works were carried out at Tai Tam Upper Dam first (2005) followed by West Col Dam (2006).

INTRODUCTION

Tai Tam Upper Dam was constructed in the 1880s and was one of the largest masonry/concrete dams in the world at the time. West Col Dam (rockfill embankment with clay core) was constructed as one of four dams for the large High Island Reservoir in the early 1980s.

Tai Tam Upper Dam

Tai Tam Upper Dam is a concrete gravity dam with masonry facing, straight in plan and it was constructed in 1883 and raised in 1887 (Figures 1 and 2). The dam is 151m long and 41m high, and the sections at the left abutment and in the central area across the old river bed are founded on solid rock. The section at the right abutment is founded partly on rock local to the central section, and on completely decomposed granite at the sloping abutment area (Figure 3 and 4). The downstream face of the dam is stepped and there are drains from the abutments onto the steps at both sides of the dam.

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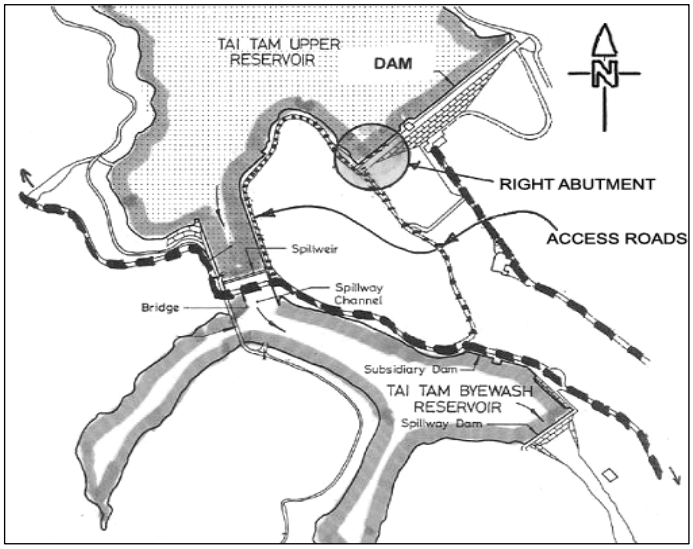

Figure 1. Tai Tam Upper Dam and Reservoir

Figure 2. Tai Tam Upper Dam – Grouting at right abutment

There was a history of leakage at the right abutment of the dam since construction, as reported by Mr James Orange (Resident Engineer) in his technical paper to the Institution of Civil Engineers in 1890. References to earlier remedial works carried out just after construction and as recommended in the 1987 Inspection Report are made below. The 1998 Inspection Report found that leakage had increased since the remedial works

recommended in the 1987 Inspection Report had been carried out. The 1998 Inspection Report recommended that a further leakage investigation be carried out. Positions for monitoring leakage at the dam are shown on Figure 3.

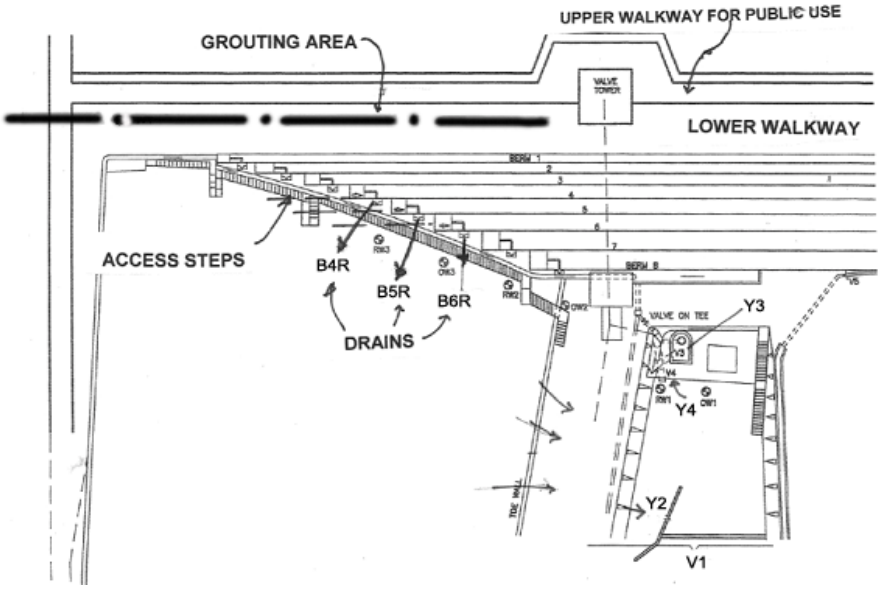

Figure 3. Tai Tam Upper Dam - Plan at right abutment

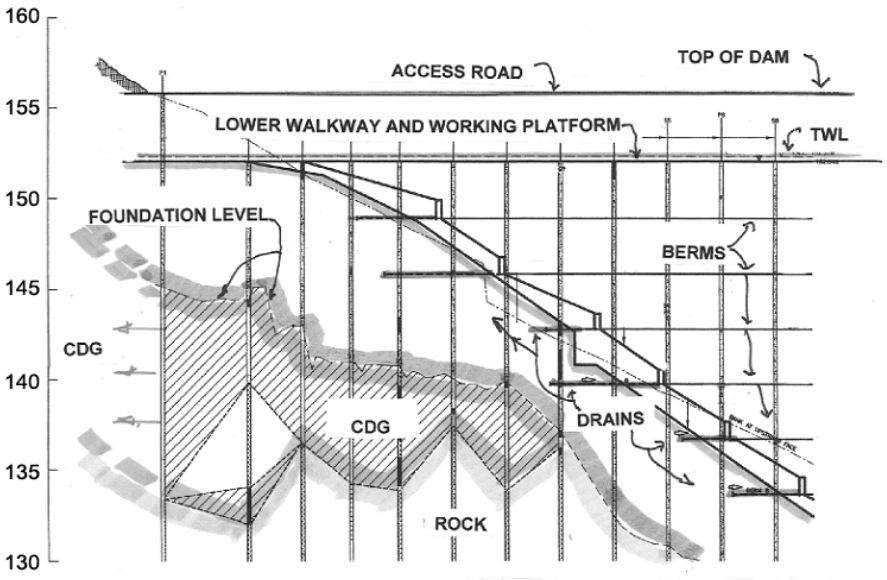

Figure 4. Tai Tam Upper Dam –Section at right abutment

Figure 5. West Col Dam - Crest and downstream face

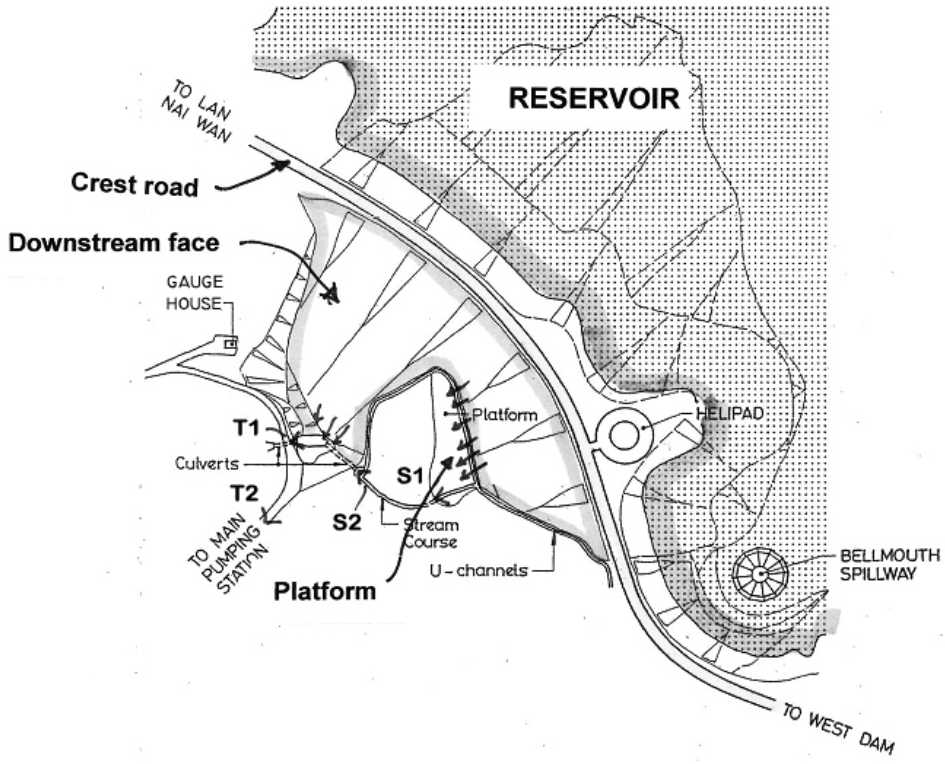

Figure 6. West Col Dam - Plan

West Col Dam

West Col Dam is a rock fill dam completed in 1979 with a clay core, curved upstream in plan, Figures 5 & 6. It is about 300 m long and 45 m high, and it is understood to be founded on residual soil overlying bedrock, Figure 7. The upstream face incorporates a knoll at the left abutment which forms a promontory with a helicopter pad. The downstream face incorporates a knoll or platform also at the left abutment which is of mainly agglomerate rock.

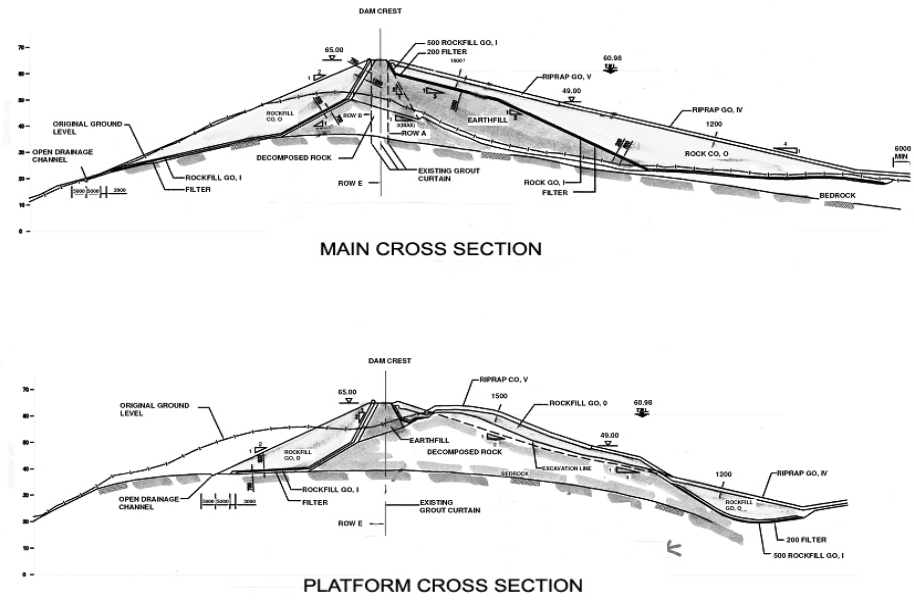

Figure 7. West Col Dam Cross Sections

Leakage appeared over the dam section at the platform at the left abutment during first impoundment with the reservoir level about 8 m below top water level. The foundation of the dam including at the platform had been grouted using Ordinary Portland Cement (OPC) during construction prior to impoundment. Further investigation and grouting works were carried out in this area under the original construction contract in 1981 again using OPC to try to ensure that no zones or channels of high permeability remained in areas of erodible decomposed rock. Leakage was not reduced by the latter works but the dam and its foundation were considered to be safe.

REVIEW OF LEAKAGE AND REMEDIAL WORKS – TAI TAM UPPER DAM

Earlier Remedial Works

There was substantial leakage at the dam after construction in the 1880s, particularly at the right abutment where the dam is founded on completely decomposed granite (CDG). A clay blanket protected by stone pitching was

laid on both sides and bottom of the valley immediately upstream of the dam just after construction to reduce and control leakage.

It was recommended in the 1987 Inspection Report that drainage flows be collected and monitored, and joints to the upstream masonry face of the concrete dam be pressure pointed. In a supplementary report to the inspection report, it was further recommended that investigation and grouting works be carried out at the right abutment foundation. Pointing of the upstream face and foundation grouting works were carried out in two phases January to August 1991 and further foundation grouting works were carried out in February to March 1993. The reservoir was substantially empty when the above remedial works were carried out and the Advisor to WSD in July 1994 concluded there had been a satisfactory improvement in control of leakage and erosion of the foundation. Discharge from the three key berm drains (B4R, B5R and B6R) at the right abutment had been reduced from 225 l/min to less than 60 l/min.

The 1998 Inspection Report found that leakage at the berm drains (B4R, B5R and B6R) had increased substantially and was still rising. The above report recommended that further leakage investigation be carried out. In the Advisory Report – Advice on Leakage at Tai Tam Upper Reservoir Dam, December 2002, the key findings were that leakage at the key berm drains had increased to 170 l/min and was still rising, and was now about 75% of the pre-grouting leakage amount. The effects of grouting had had been substantially lost by erosion of the grout curtain below the dam and the surrounding ground. Deposits of sand, silt and soft grout were found at the drainage outlets. It was concluded that leakage at the right abutment would be likely to increase at least to the pre-grouting level and erosion of material below the abutment would continue.

The main concern was with the stability of the dam at the right abutment from continuing erosion of the foundation that could affect support to the dam and lead to uncontrolled changes in seepage conditions. The Advisory Report, December 2002, recommended that remedial works be carried out to the upper part of the right abutment below the dam to substantially reduce and control leakage and to prevent further erosion of the foundation. Leakage at the left abutment and the central section of the dam, which are founded on solid rock, did not give cause for concern.

<u>Investigation and Remedial works</u>

Different approaches were considered in the Advisory Report and a “multi-line” grout curtain was recommended using cement and chemical grouts for formation of an effective cut-off and ground consolidation below the dam. Cement grouting of the foundation with OPC had been adopted on a

previous occasion and had not been effective in permanently reducing leakage. A three line grout curtain was proposed for the new grouting works to provide a wider grouted zone, Figure 8, and with grouting works being carried out with the reservoir in service within a range of specified levels in order that effects of grouting could be seen as work proceeded.

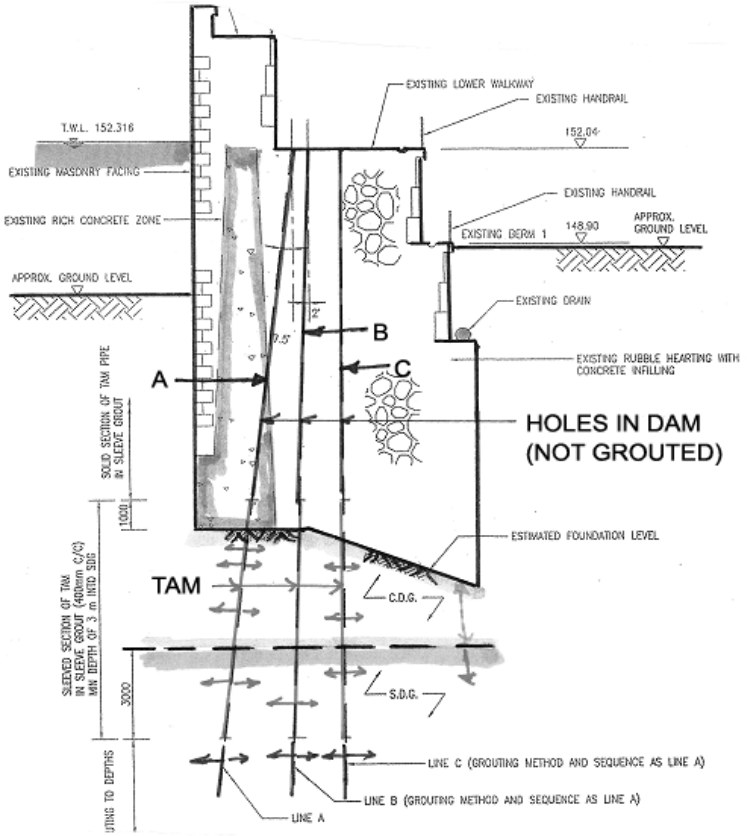

Figure 8. Tai Tam Upper Dam - Typical grouting Section

The scope of the investigation and remedial works covered (a) investigation works by seven boreholes (vertical and inclined) in advance of grouting; (b) construction of a multi-line grout curtain including control holes for testing effectiveness of grouting; and (c) monitoring of drainage discharges throughout the periods of both investigation and remedial works. Tracer tests were carried out in investigation holes to check connections to the downstream drainage system. Trial grouting was also carried out in investigation holes to determine the most effective grouting method for different ground conditions, that is “tube-a-manchette” (TAM) or “open hole” fissure grouting, and to give the contractor experience of using the specified grouts ,which were all imported to Hong Kong.

Grouting materials specified for the contract were as follows:

(a) Ordinary Portland Cement (OPC) to BS12 (min fineness of 300 m^2/kg) – for sleeve grout for the TAM tubes and filling holes.

(b) Superfine Portland Cement to BS 12 (min fineness of 650 m^2/kg) – for injection into soil and rock – RheoChem 650 or approved equal.

(c) Ultrafine Portland Cement to BS 12 (min fineness of 900 m^2/kg) – for injection into soil and rock – RheoChem 900 or approved equal

(d) Chemical grout (low viscosity, strength 0.5-50 MPa, and gel time of 1 min. to 24 hours) for injection into soil and rock – Insta Grout Con (3-component acrylic grout with accelerator).

Previous unsuccessful grouting at Tai Tam Upper Dam in 1991 and 1993 had been carried out with OPC to BS 12 but on this occasion it was proposed that OPC would only be used for sleeve grout and filling grout holes. The typical grouting cross section is shown on Figure 8 where lines A and C are the upstream and downstream lines and line B is the central line.

TAM primary holes (3m c/c) in lines A and C in the completely decomposed granite (CDG) below the dam were grouted and then TAM secondary holes at 1.5m c/c. TAM holes were extended in stages for fissure grouting in the more solid CDG and slightly decomposed granite (SDG). Tertiary holes for TAM and fissure grouting at 0.75m centres were added as required. Insta Grout and RheoChem 900 cement were normally used for TAM grouting and RheoChem 650 and 900 cements for fissure grouting. Where sleeve opening pressures in TAM grouting were high in CDG, “open hole” fissure grouting in downward stages was adopted for more effective grout penetration. About 45m of the foundation below the dam was grouted plus an angled section into the abutment beyond the dam. High grouting pressures were used to maximize grout penetration.

Summary details for both TAM and fissure grouting were as follows:

(a) Number of grout holes – 83.

(b) TAM grout quantities – RheoChem 650 – 9.95 t, RheoChem 900 – 30 t, and Insta Grout - 12 t.

(c) Fissure grout quantities - RheoChem 650 – 5.3 t, RheoChem 900 – 26.5 t, and Insta Grout – 21.4 t.

(d) Total grout weight – 105 t (2.33 t per metre of cut-off).

A review of leakage showed that there was a steady reduction in leakage as grouting progressed, and that there were some early variations when leakage was reduced and then increased, due to erosion of the grout before further grouting was carried out with appropriate quick setting grout mixes to seal known leakage areas. Tests in control holes showed that the maximum specified permeability (k) of 5 lugeons was met, and tests on piezometers installed in control holes gave "k" values of about 1 lugeon and less.

Final Impoundment Test was carried out in Sept - Oct 2005 and results were satisfactory. The total discharge from the key drains on the downstream face of the dam with the reservoir at top water level was 26 l/min, which was about 10-15 % of the original discharge. Discharge when the reservoir was 3.5m below top water level was 21 l/min. Results indicated that the residual flow at the drains was made up of minor seepage below the dam at the right abutment, and from the hillside downstream of the dam. The source of the latter flow was likely from the reservoir on the other side of the hill downstream of the right abutment of the dam.

Corresponding drainage results in June 2006 with the reservoir just below top water level was 11.1 l/min, which reduced to 5.4 l/min in June 2007 indicating that further self sealing had occurred. The reservoir is generally full in the summer (wet season) and consequently it is difficult to obtain readings at high reservoir levels which are not affected by rainfall to some degree. Discharge readings in June 2009 confirmed that the grouting works are still effective. In summary, use of superfine and ultrafine cement grouts and acrylic grout have been effective in substantially reducing leakage and stopping internal erosion of the foundation below the dam.

REVIEW OF LEAKAGE AND REMEDIAL WORKS - WEST COL DAM (HIGH ISLAND RESERVOIR)

Earlier Remedial Works

Reference is made above to the problem with leakage at West Col Dam that occurred during first impoundment of the High Island Reservoir. The main body of the dam is about 50m high and part at the left abutment rests on a rock platform about 20 m below the crest. Grouting of the foundations was originally carried out in October 1974 and July 1975 after the base of the core trench was excavated down to highly decomposed rock and to within 2m of final excavation depth. There is a clay blanket below the upstream shoulder over the main part of the dam which increases the seepage path, but there was no clay blanket below the upstream shoulder at the platform section of the dam. Grouting was carried out by the down stage method with Ordinary Portland Cement (OPC).

The dam at the platform is underlain by porphyritic tuff of the High Island Division, and the depth and degree of weathering below the dam varies, see Figure 9. The High Island Division is underlain by Lan Nai Wan Division which consists of rhyolitic agglomerates in this area which outcrop at the platform at the downstream side of the dam. There are tuffaceous sediments at the junction between the High Island and Lan Nai Wan Divisions.

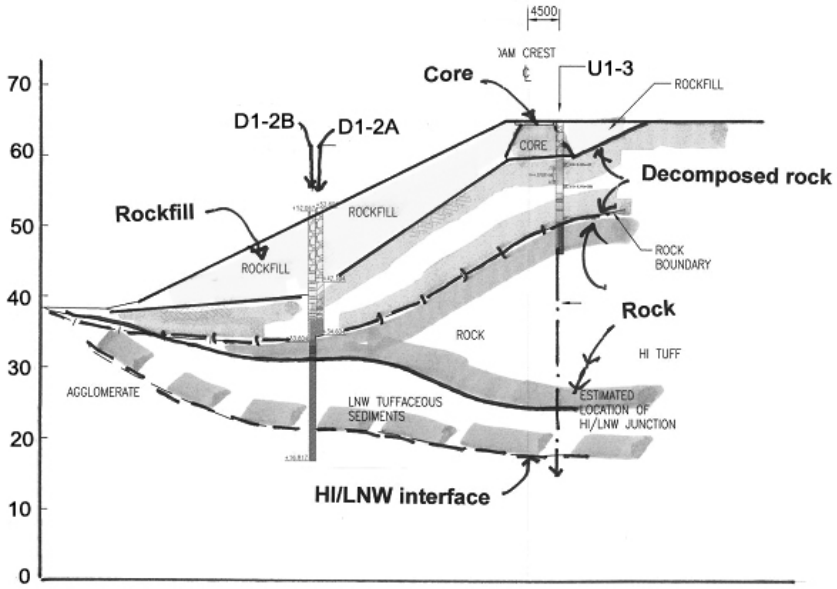

Figure 9. Ground condition below the dam

The reservoir first filled to about 8m below top water level during the 1979 wet season and seepage at the platform from the downstream toe of the dam was about 170 l/min. More site investigation was instructed and further grouting works commenced in June 1980. The purpose of the second grouting operation was to ensure that no zones or channels of high permeability remained in areas of erodible decomposed rock. The agglomerate outcrops along the edge of the platform and causes seepage to discharge from overlying formations. Grouting pressures were initially limited to 0.5 times overburden pressure for the first stage below the embankment core and to 0.75 times overburden pressure for further stages. The latter pressure was later raised to overburden pressure to try and increase the effectiveness of grouting.

It was found that the additional grouting did not reduce seepage at the reservoir levels for which comparisons were available. Grout stages with high Lugeon values were found in upper zones of decomposed rock and in the region of the High Island and Lan Nai Wai junction. Grout takes in the latter stages were very low indicating that grout could not penetrate

decomposed rock as readily as water. It was considered that the dam and its foundation were safe.

The reservoir reached full or nearly full over eight successive years, 1994 to 2002, and records were referred to the Advisor for comment in December 1998 with a review of leakage continuing to 2002. In the Advisory Report, High Island Reservoir, Advice on Leakage West Col Dam, December 2002, the key finding was that leakage had increased due to deterioration of the foundation between late 1998 and 1999 and deterioration was consistent with enlargement of small flow paths by internal erosion, or by breakdown of the earlier grout curtains formed by grouting using Ordinary Portland Cement. The estimated maximum discharge during sustained periods of near full conditions was at least 670 l/min (gauge S1 at platform), which was an increase of about 40% from first filling in 1983. A review of piezometer readings also indicated that leakage was occurring within the region of the High Island tuff rock and above the Lan Nan Wai junction with the agglomerate but this conclusion was not definitive.

It was concluded that standard cement grouting techniques adopted during construction had not been effective in controlling foundation leakage and this was further aggravated by limits imposed on grouting pressures below the clay core. Increased leakage and changes in pore water pressures were also indicative of foundation erosion, and were a warning that the safety of the reservoir may be endangered.

The Advisory Report, December 2002 recommended that investigation and remedial works be carried out below the dam in the platform area to substantially reduce and control leakage and to prevent further erosion of the foundation. Seepage from the main section of the dam, where there is a clay blanket below the upstream face, did not give cause for concern.

Investigation and Remedial Works

It was considered that the most appropriate method to carry out the remedial works would be by further grouting using finer cements and chemical grouts with low initial viscosity, preceded by an investigation stage to obtain more information on foundation and grouting conditions.

The scope of the works proposed in the Advisory Report, December 2002 covered (a) investigation works by six boreholes on the line of the proposed cut-off and eight boreholes at about mid-height of the downstream shoulder above the platform with a view to intercepting seepage at two levels from tracer tests in the upstream investigation holes; (b) construction of a multi-line grout curtain including control holes for testing effectiveness of grouting; and (c) monitoring of drainage discharges throughout the periods

of both investigation and remedial works. As for the Tai Tam Upper Dam, tracer and grout tests were carried out in the crest investigation holes, and internal inspections by camera were also made. A key factor was again to determine the most effective grouting method ("Tube-a-manchette" (TAM) or "open hole" fissure grouting). An objective was to do as much open hole fissure grouting as possible but to use the TAM method at the core/foundation junction and for a short depth below the junction.

The multi-line grout curtain (three lines) was located towards the upstream edge of the clay core at foundation level, which required holes from ground level to the core to be drilled and cased through rip-rap stone. This allowed all holes on the dam crest to be located upstream of the crest access road and drilling through the core to be minimised.

The same grouting materials were specified for the contract as had been used successfully for Tai Tam Upper Dam. A grouting typical cross section is shown in Figure 10 , with lines A and C being the upstream and downstream lines respectively and line B the central line. It was specified that the reservoir water during the grouting works should be kept above 55m PD (that is about 6m below overflow level) to check the impact of grouting during grouting works. The minimum level of 55m PD was later changed to 50m PD because of low reservoir levels when grouting started.

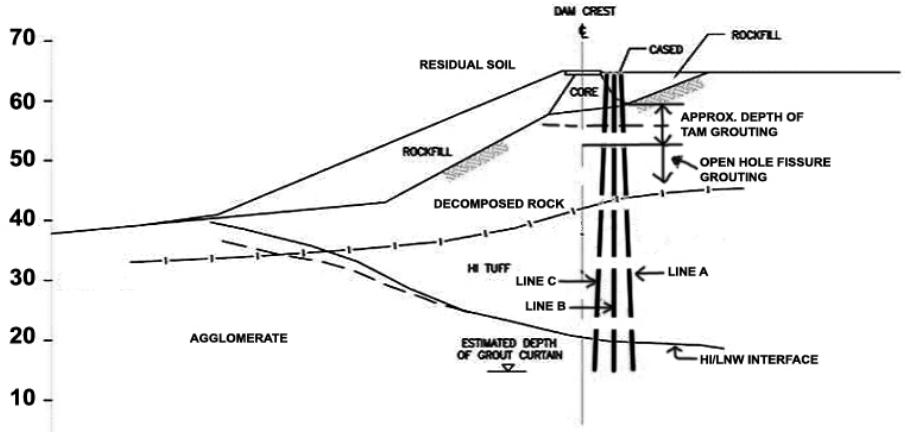

Figure 10. West Col Dam - Typical grouting section

TAM primary holes (6m c/c) in lines A and C in residual soil and decomposed volcanic rock below the dam were grouted and then TAM secondary holes at 3m c/c. TAM holes were extended in stages for fissure grouting in the more solid volcanic rock. Tertiary holes for TAM and fissure grouting at 1.5m centres were added as required. Insta Grout was used for TAM grouting immediately below the clay core with pressures up to 4-6 bar for about 4-5 stages of 0.4m depth. Ultrafine cement grout

RheoChem 900 was used for the rest of the TAM grouting with pressures rising up to 20 bar.

Ultrafine and superfine cement grout (RheoChem 900 and 650 respectively) were used for fissure grouting below the TAM tubes with RheoChem 650 being used where grout takes were large. Insta Grout was also used in fissure grouting where a quick set was required. High grouting pressures were used for fissure grouting (20 bar) to maximise grout travel and negligible heave at the ground surface was found.

A length of 120m length of the dam foundation was grouted local to the platform, plus additional holes in line A at the south abutment local to a geological fault. The depth of TAM grouting varied between 5m to 10m, and the depth of fissure grouting below TAM grouting was generally in the range 30m to 40m. Total depths into the underlying agglomerate were about 50m for most holes. Very few connections were made to the drainage system on the downstream slope during grouting. There were significant grout takes in both TAM and fissure grouting over the full depth of the curtain. Thirteen stages had takes in fissure grouting of over 200 l/min; 60 were in the range of 100-200 l/min and 232 were in the range of 50-100 l/min. Most stages had some grout take.

Summary details of for both TAM and fissure grouting were as follows:

(a) Number of grout holes – 177.

(b) TAM grout quantities – RheoChem 650 – 1t, RheoChem 900 – 175t, and Insta Grout - 85t.

(c) Fissure grout quantities - RheoChem 650 – 138 t, RheoChem 900 – 81t, and Insta Grout – 0.5t.

(d) Total grout weight – 480t (4t per metre of cut-off).

A review of the leakage showed that there was a steady reduction in leakage as grouting progressed after account was taken of rainfall effects. Tests in control holes showed that the specified maximum permeability (k) of 5 lugeons was met. Tests on piezometers installed in control holes indicate “k” values of about 1 lugeon and less. The reservoir rose fairly quickly from May to Sept 2006 to about 1.85m below top water level. The estimated discharge at the platform at top water level was about 200 l/min which is about 30% of estimated discharge at top water level before grouting works were carried out. It was considered that substantial additional grouting would be required to further significantly reduce leakage.

Review of drainage records in mid 2008 confirmed that the performance of the grouting works was satisfactory and there appeared to be further self sealing such as found at the Tai Tam Upper Dam. In Sept 2008, the reservoir reached about 1.75m below top water level and the discharge at the platform was only about 105 l/min after an extended dry spell of about eight days which would remove rainfall effects and indicate a discharge of about 120 l/min at top water level. The reservoir water level in 2009 has been fairly low (maximum level about 5.7m below top water level) but again the drainage results again show self-sealing.

In summary, use of superfine and ultrafine cement grouts and acrylic grout have again been effective in substantially reducing leakage and stopping internal erosion of the foundation below the West Col Dam

ACKNOWLEDGEMENT
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