Grouting to reduce seepage at Neckartal Dam, Namibia

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Neckartal Dam is an 80m high RCC curved gravity dam in Namibia that spilt for the first time in January 2021. As the dam filled to full supply level (FSL), usual increases in seepage were observed, but all measured seepage rates were within stipulated acceptable limits for a large concrete dam.

Seepage from the dam is monitored at eight v-notch gauges in the dam galleries. During the course of the year, measured seepage at the gauges remained relatively constant or had even slightly decreased until May 2021, when seepage measurement from the upper left bank gallery v-notch gauge steadily increased to a rate that was no longer considered acceptable.

High seepage was observed predominately from a single drainage hole in the left bank, where the dam wall contacts a steep left bank foundation.

Volumetric changes occur within an RCC dam during the hydration and temperature dissipation cycle. Temperature rises due to cementitious hydration and will peak within the first couple of weeks following placement. However, once developed, it takes several years to dissipate to a steady state seasonal equilibrium temperature.

It is important for the safety of the dam that major seepage paths be sealed to avoid potential erosion of the foundation at the position of the open joint and/or flooding of the dam galleries, which may result in damage to electrical equipment for operating the hydromechanical equipment and the instrumentation for monitoring the behaviour of the dam.

In this paper, the authors describe the evaluations made and the approach followed to successfully reduce the seepage observed to an acceptable rate by undertaking sequenced precision drilling and grouting of a specific target area of the dam foundation post-construction. The grouting operation was particularly difficult, considering the high water pressures experienced from the full dam and several seepage paths through the foundation. The use of thick, stable cementitious grout, combined with systematic drilling, water pressure testing and grouting, was successful in reducing flow significantly.

1 INTRODUCTION

Neckartal Dam is located on the Fish River, a tributary of the Orange River. The project will supply bulk water to an irrigation scheme located 40 km southwest of Keetmanshoop in Namibia. Keetmanshoop has a desert climate. The daytime temperature often rises above 40°C during the summer, and the mean annual precipitation is less than 150 mm. The Employer was the Namibian Ministry of Agriculture, Water and Forestry. The Contractor was Webuild S.p.A. (formerly Salini Impregilo). Knight Piésold Consulting (Pty) Ltd undertook the engineering design and site supervision.

Neckartal Dam is the largest dam in Namibia and the eighth largest dam in southern Africa in terms of storage volume. It is the largest dam that has been recently constructed in southern Africa. Neckartal dam is 80 m high, with a crest length of 518 m and a gross storage capacity of 857 million m^3. The main dam wall contains approximately 900 000 m^3 of RCC. Construction commenced in September 2013, and the RCC placement was completed in May 2018. The taking-over certificate was issued in September 2019.

Figure 1. Neckartal Dam view from downstream.

Following closure, Neckartal Dam filled rapidly during the 2020 to 2021 wet season and spilled for the first time in January 2021. Seepage from the dam is monitored at eight v-notch gauges (VN001 to VN008) located inside the dam's drainage galleries. As the dam filled to the Full Supply Level (FSL), an increase in seepage was recorded, which was expected. Seepage rates were within the stipulated acceptable limits and were observed to remain constant or decreasing until May 2021, when a sudden increase in measured seepage flows was observed at VN 008, installed in the upper left bank gallery. Measured seepage steadily increased from 3 ℓ /s to 12 ℓ/s over a 4-month period at this gauge before stabilizing at the end of 2021. The seepage rate peaked at an unacceptable level of 12.80 ℓ/s in August 2022. High seepage rates of over 10 ℓ/s are above the trigger limits set in the Neckartal Dam O&M manual, which require "action to be taken". The seepage was observed predominately from a single drainage hole (F152 indicated in Figure 2) in the left upper drainage gallery.

It was surmised that the seepage originated from a stress relief/ joint movement in the left bank foundation, induced by either temperature changes in the dam wall and its foundation since construction or progressive erosion of a concentrated seepage path.

It is important for the safety of the dam that high seepage paths be sealed by grouting to avoid progressive erosion of the foundation at the position of the open joint and/or flooding of the dam galleries, which may result in damage to some of the important instrumentation and monitoring equipment installed. Figure 2 below provides the location and photograph of the drainage holes with F152 with the strongest flow, respectively.

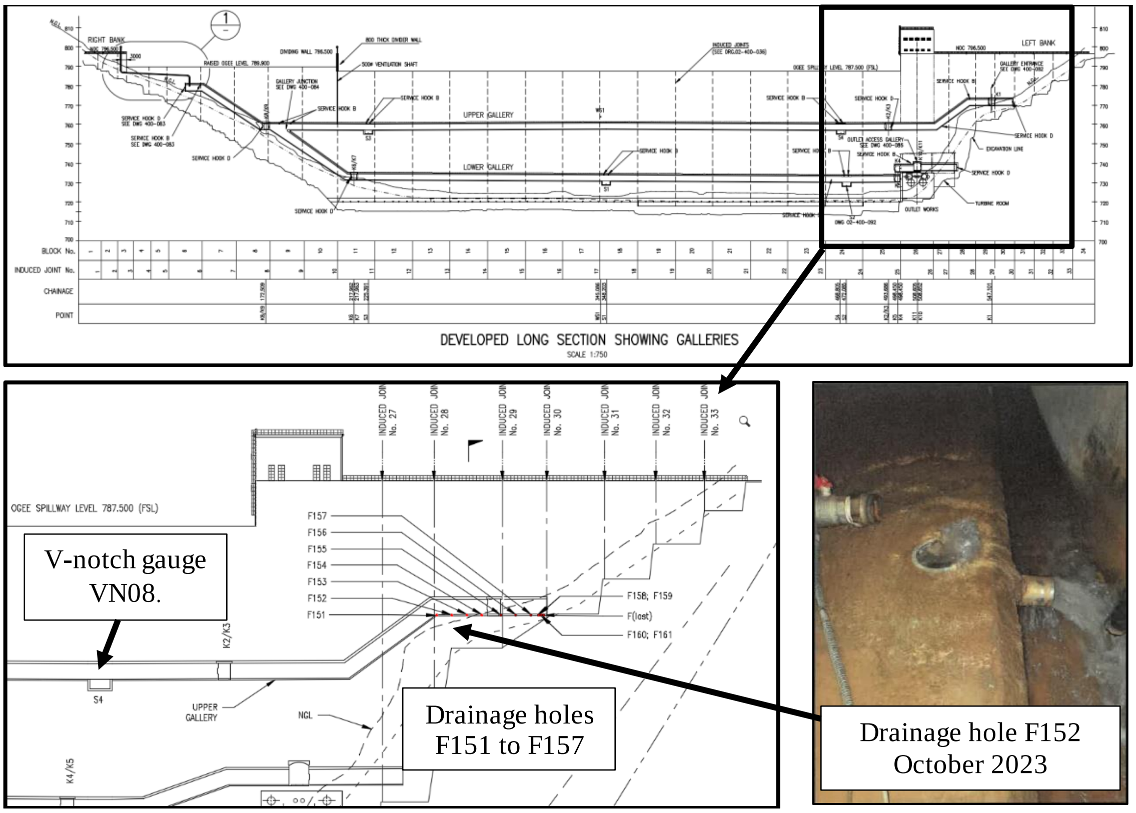

Figure 2. Location of drainage holes in the left bank (seepage mainly from drainage hole F152).

2 INSTRUMENTATION RESULTS

Knight Piésold was commissioned by the dam operator to investigate the potential origin of the seepage and to determine methods to reduce the seepage in the upper left bank gallery. This included an analysis and interpretation of the dam instrumentation results, geological records, foundation mapping and grouting records made during the construction of the dam.

2.1 *Seepage measurement*

Seepage measurement records at the eight gauges indicated that seepage increased as the dam filled rapidly from level 750 mASL to 787.5 mASL. This was expected due to the higher incremental water pressure, and the change was observed uniformly at four of the eight gauges. All seepage was within the specified limits in January 2021 after the first filling of the reservoir.

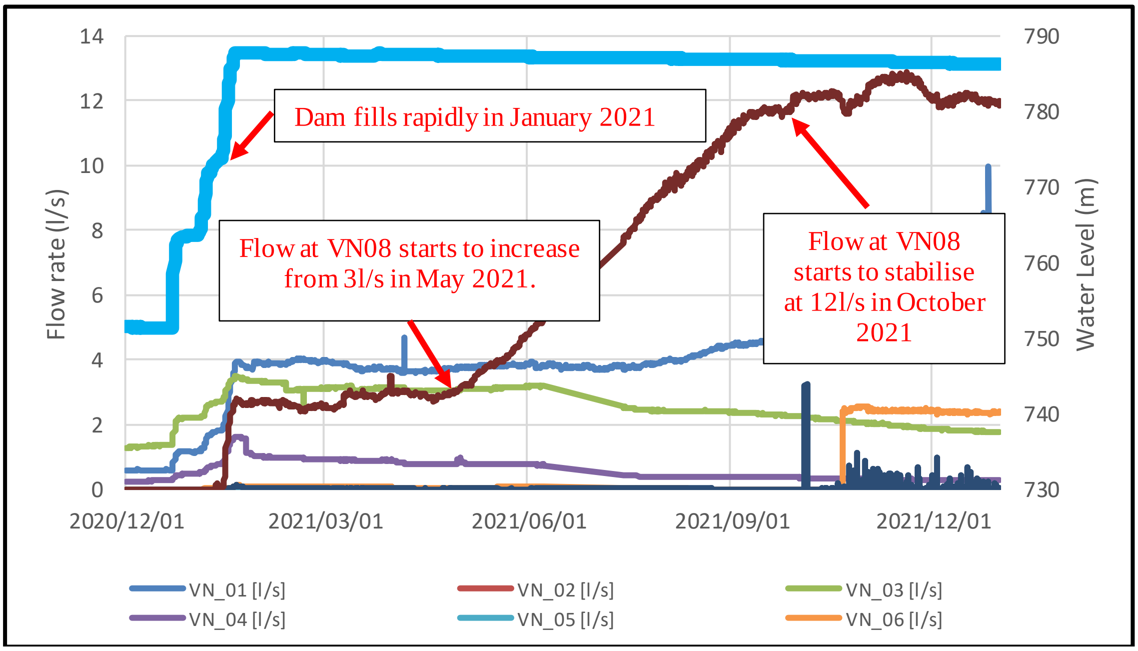

Figure 3. V-notch gauge flow rate and water levels from December 2020 to December 2021

However, measured seepage at VN008 increased rapidly at the beginning of May 2021, four months after first filling and continued to increase until October 2021. This increase in seepage was of concern as, at the time, it was not known whether it would continue to rise, stabilize or again reduce. Seepage from the adjacent gauges had remained relatively constant over that period. Seepage trends were closely monitored and found to stabilize by October 2021 but remained above the acceptable limit. Figure 3 indicates the dam water levels during the first filling and the seepage measured at each v-notch weir. Because the increase in seepage was recorded in May and the stabilization occurred in October, coinciding with the arrival of the colder and hotter seasons, respectively, it was assumed that differential temperatures of the concrete and foundation may influence the observed seepage rates.

2.2 *Dam Temperatures and Induced Joint openings on the dam axis*

The induced joint openings and temperatures are measured with #56 Long Based Strain Gauges (LBSG) installed mainly at two levels in the dam, viz at 730 mASL and at 757 mASL. The LBSG positions at elevation 757 mASL are shown in Figure 4.

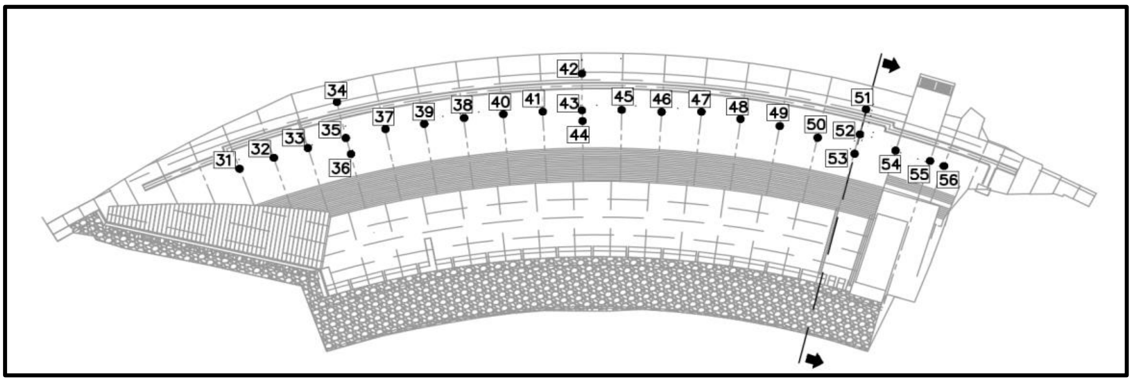

Figure 4. LBSGs at elevation 757 mASL – Location

From the LBSGs temperature records in the centre of the dam section and along the dam axis, the temperature has continuously decreased at a rate of about one degree a year. The average temperature of the dam core was approximately 30°C after placement in 2017. The current dam core temperature ranges from approximately 22 to 24°C in 2024, depending on the section thickness and foundation proximity. This has resulted in a six-to-eight-degree temperature decrease over seven years in the dam core. During 2021, the dam temperature decreased by almost two degrees after the rapid reservoir filling. The temperatures measured across joints # 18 to # 27 at the LBSGs #45 to #50, #52, #54, #55 and #56 are shown in Figure 5 below.

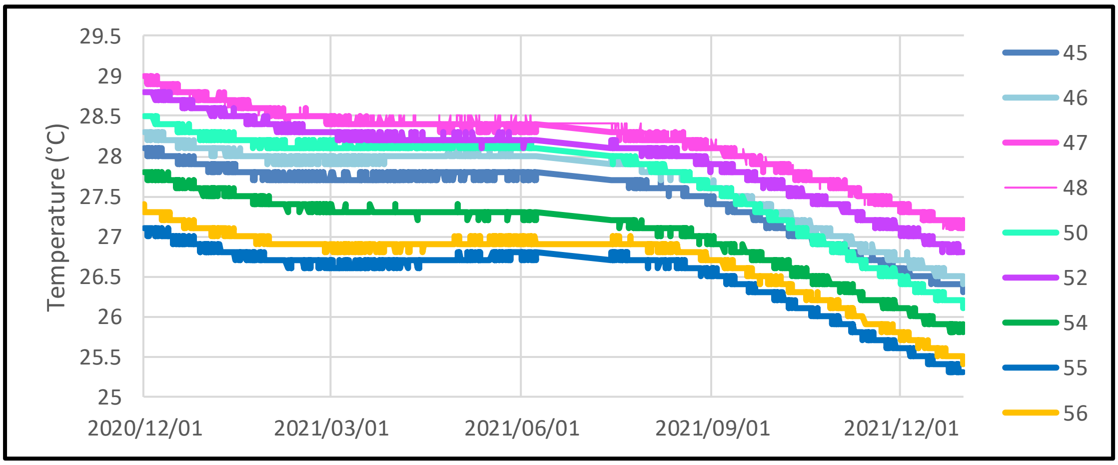

Figure 5. LBSGs at elevation 757m – Temperatures

The LBSG indicated no opening or closing during 2021 except for joint 54, which opened by less than 0.1 mm during the first filling in January 2021. From the joints being monitored, no joint showed any significant movement, which could explain the seepage at VN008 increasing steadily between May and October 2021. The movements across joints #18 to #27 at LBSGs #45 to #50, #52, #54, #55 and #56 are shown in Figure 6 below.

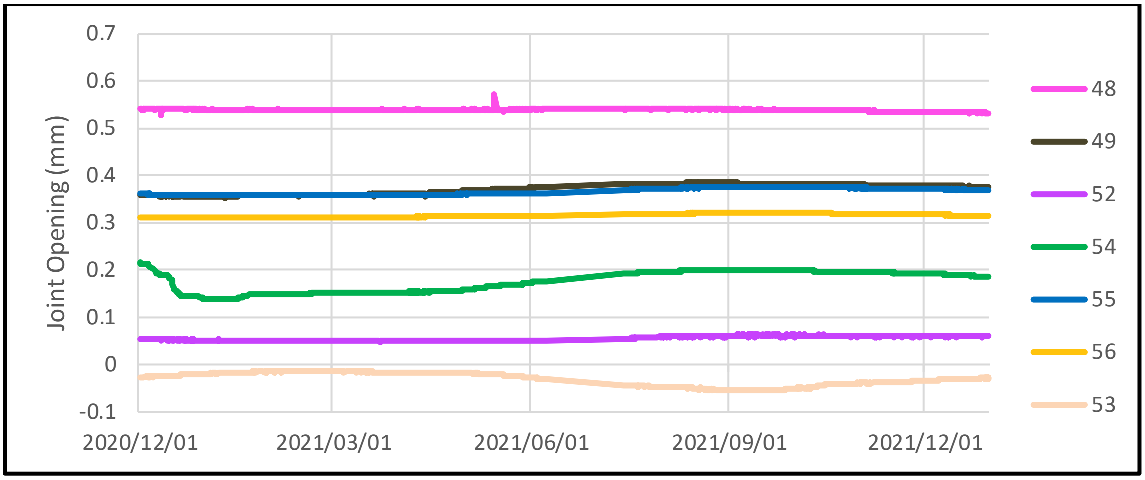

Figure 6. Neckartal Dam: LBSGs at elevation 757m – Joint opening

2.3 *Dam Temperatures and Joint openings perpendicular to the dam axis*

There are nine LBSGs in joint 24. Their positions are shown in Figure 7. The LBSG positions are at elevations 730 mASL and 757 mASL and are evenly spaced between the upstream and downstream faces of the dam.

LBSG #29 and #53 near the downstream face and LBSG 51 on the upstream face clearly show the impact of the ambient and water temperatures on the outer surface of the dam. LBSG #24 on the upstream face was already submerged in 20 m deep water from the previous year's wet season. The LBSGs closer to the dam core indicated a constant linear decrease over the whole year. The temperatures measured across joint #24 are at LBSGs #24 to #29 and #51 to #53 as shown in Figure 8.

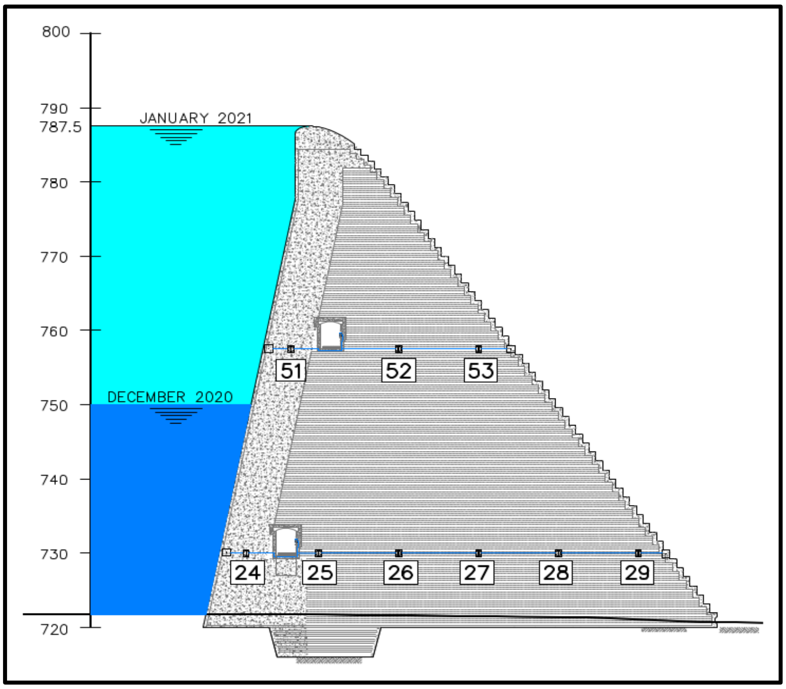

Figure 7. Dam Cross-Section Joint #24: LBSG on joint 24 at 730mASL & 757mASL

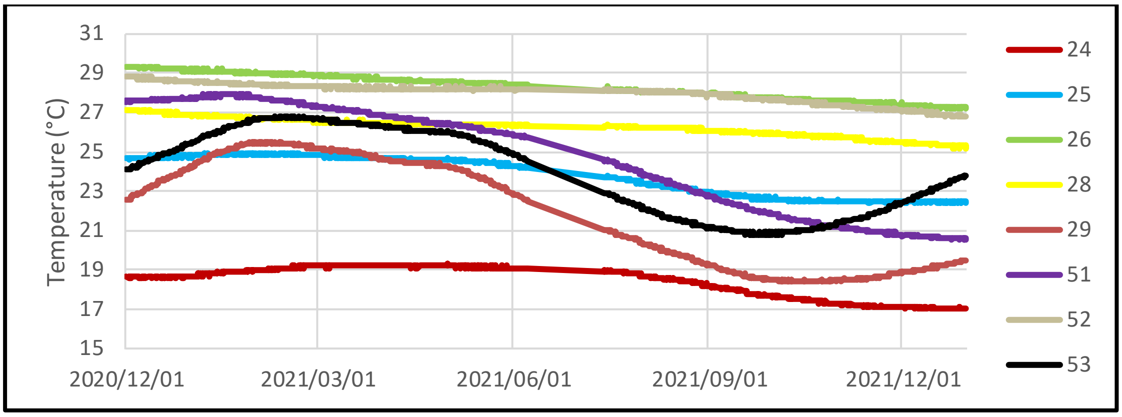

Figure 8. Neckartal Dam: LBSG across joint 24 at elevations 730mASL & 757mASL -Temperatures

The only two LBSG to show a significant movement during 2021 were the two gauges close to the dam's downstream face. LBSG #29 indicated an opening of approximately 0.3 mm, and LBSG #53 indicated an opening of approximately 0.15 mm. Thus, the only opening of joint #24 was on the dam's downstream face. Neckartal Dam is northwest-facing; therefore, the downstream face is exposed to significant warming from the sun. The movements across joint #24 at LBSGs #24 to #29 and #51 to #53 are shown in Figure 9 below.

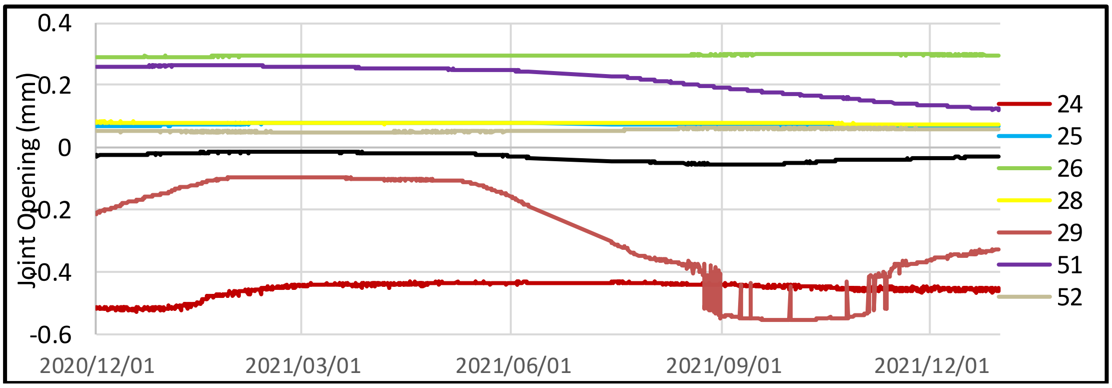

Figure 9. Neckartal Dam: LBSGs across joint 24 at elevations 730mASL & 757mASL -Temperatures

The opening of the downstream joint at LBSG #29 & #51 is consistent with the period of increased flow rates from May to October 2021.

3 GEOLOGY AND GROUTING RECORDS

Neckartal Dam is underlain by red sandstone and shale of the Gross Aub and Nababis Formations of the Fish River Subgroup, Nama Group. These sedimentary rocks can genetically be subdivided into a number of regressive cycles of sedimentation, mainly of an alluvial fan origin. Numerous, often repetitive, changes in lithology occur abruptly or gradually. The geological contacts between rock types at Neckartal are often not well defined but consist of a gradual transition with depth.

The rock formation below the dam foundation is mainly comprised of sandstone with siltstone bands, becoming siltstone with sandstone bands below the dam foundation at a depth of 10 m. The banded sandstone and siltstone bedrock at the dam site is horizontally bedded, and mica on the bedding planes resulted in relatively low shear strength on these joints. From the geological mapping of the foundation of blocks 28 and 29, there are two dominant joint sets, which are sub-vertical with a strike direction of approximately 240˚ and 135˚ from magnetic north, respectively. A thin joint infill of between 0,5 mm to 2 mm comprising chlorite and calcite occurs in linear joints. Minor shear zones occur in localized areas in the thick sandstone layers with a thin mica layer (1-3 mm) present on the bedding planes.

The original grout curtain between Block 26 and Block 34 was drilled from the lower drainage gallery and top of RCC surface. The grout holes were drilled 20° from the vertical towards the left flank, and the drilling stage depth varied between 18 m and 68 m.

The average lugeon (Lu) value for the grout holes across the left flank is generally less than 2 Lu, with isolated zones of high permeabilities recorded in the first 10 m of S75 and P72, with Lu values of 6,9 Lu and 8,9 Lu respectively. The corresponding grout takes for S75 and P72 were 408 litres and 240 litres, respectively. These were the highest grout takes recorded along the left flank, and none of the other grout curtain holes in this area showed similar high grout takes.

The average grout take per sequence per stage is shown in Figure 10. Virtually tight rock mass conditions were encountered on the steep left flank across all stages. The results of water pressure tests gave low Lugeon values of generally less than 0,8 Lu with corresponding grout takes averaging 1,6 kg/m.- From the left bank grout take records, Block #29 (nearest to the observed high seepage zone) indicates a slightly higher comparative Lu to the adjacent blocks. However, under block #28, the foundation had low lugeon values.

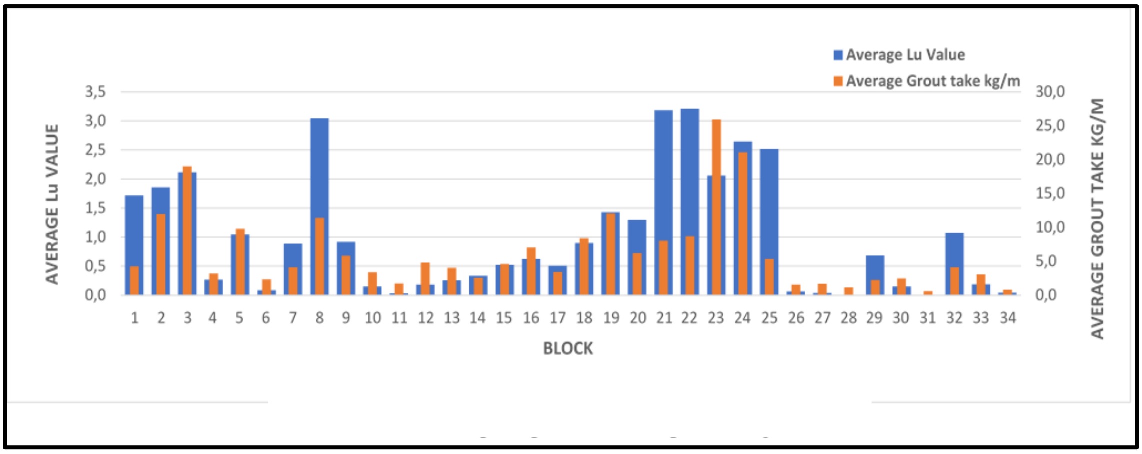

Figure 10. Neckartal Dam: Average Lugeon and grout take per block during construction.

4 REMEDIAL GROUTING PLAN

The drilling and grouting contractor (Rostruct), who did all the original drilling and grouting at Neckartal Dam, was approached to assist with the drilling and grouting required to attempt to seal the high seepage in the left bank gallery. The drilling and grouting operations were scoped, and unit rates were agreed upon for the work required. The scope of work required packer testing to determine the elevation of the seepage, which would assist in targeting the grouting and included drilling a set of primary grouting holes at 8 m spacing with secondary grouting holes midway between the primary holes to the level of the original grout curtain depths. An allowance was made for additional tertiary and quaternary holes. If the existing drainage holes became blocked, these would be re-drilled from the crest through the drainage gallery. The holes for grouting would be drilled using the rotary core drilling method because of reinforcement in the crest and in the drainage gallery precast concrete roof sections. Drilling was done from the dam NOC to intersect the foundation because of confined space.

5 SITE INVESTIGATIONS

Following establishment on site, the first task was to determine the elevation from where the seepage was originating. It was speculated at that time that the seepage could be originating from an opened joint in the RCC, the contact between the RCC or the foundation or from a joint in the rock mass below the dam foundation in the left abutment. The seepage origin investigation included packer tests conducted in the three drain holes that showed the most flow, F151 (situated close to the top of the gallery stairs), F152 (strongest flowing) and F153 (closer to the left abutment) as indicated in Figure 2 above. Testing comprised the isolation of sections of the hole by means of a pneumatic packer. The packer has a length of about 500 mm, and the seepage depths estimated below must, therefore, be seen to have an accuracy of +/- 250 mm at best.

F152: This drainage hole was tested first, and it was found that the depth at which water enters the hole occurs between 8.0 m and 8.2 m below the gallery floor level. It is possible that some water also enters the hole at depths below 8.2 m, but based on the visual observation of the flow rate, it appears most of the flow originated from this depth. Based on the as-built drawings, this depth corresponds to approximately the foundation interface. However, considering the effect of the steep foundation slope, it is difficult to determine the exact foundation contact level. It was therefore, concluded that the seepage was either from the foundation contact or the rock mass just below the foundation contact.

F151: The packer was lowered to a depth of 22 m in 1 m increments without managing to seal the inflow of water. The water flow was however sealed with a packer at a shallow depth of less than 1 m. This confirmed that the source of the flow in F151 was from below the gallery floor slab. It was concluded that the source of flow in F151 was from F152, which pushed water underneath the gallery floor slab towards F151.

F153: The depth at which water enters the hole occurs between 10.0 m and 10.5 m below the gallery floor level. Based on the available information, this depth corresponds to a depth of approximately 2.5 m below the foundation contact into the abutment.

6 DRILLING AND GROUTING

The following activities were undertaken to seal the prominent seepage at F152 and adjacent drainage holes and to decrease the overall rock mass permeability on the upper left flank.

6.1 *Drilling*

The drilling program was revised after the packer test results were available, reducing the depth of the grouting holes to target the seepage at higher elevations.

The drilling was completed in the following stage lengths:

- First stage: 10 m into the foundation rock from the concrete-rock interface
- Second stage: 20 m into the foundation rock (only for selected holes)

The grouting sequences for additional tertiary and quaternary holes were dependent on the water pressure test results of the primary and secondary holes. The "splitting holes" comprised tertiary (T), 3 Quaternary (Q) and 3 Quinary (Qi) holes spaced at 2 m, 1 m, and 0.5 m, respectively.

A total number of 20 grout holes (5 Primary, 5 Secondary, 4 Tertiary, 3 Quaternary and 3 Quinary boreholes) were drilled. The positions of these boreholes were determined by the Engineer based on the water pressure tests and the grout takes.

Drilling and grouting were conducted from the dam wall crest, and the grout holes are positioned so that the curtain is about 1 m upstream of the gallery and the original grout curtain. The grout holes, therefore, involve drilling significant lengths through concrete. Drilling was generally temporarily terminated when water losses were encountered to conduct water pressure tests and grouting, before continuing to the required depth. The location, direction, and depth of the actual boreholes are shown in Figure 11.

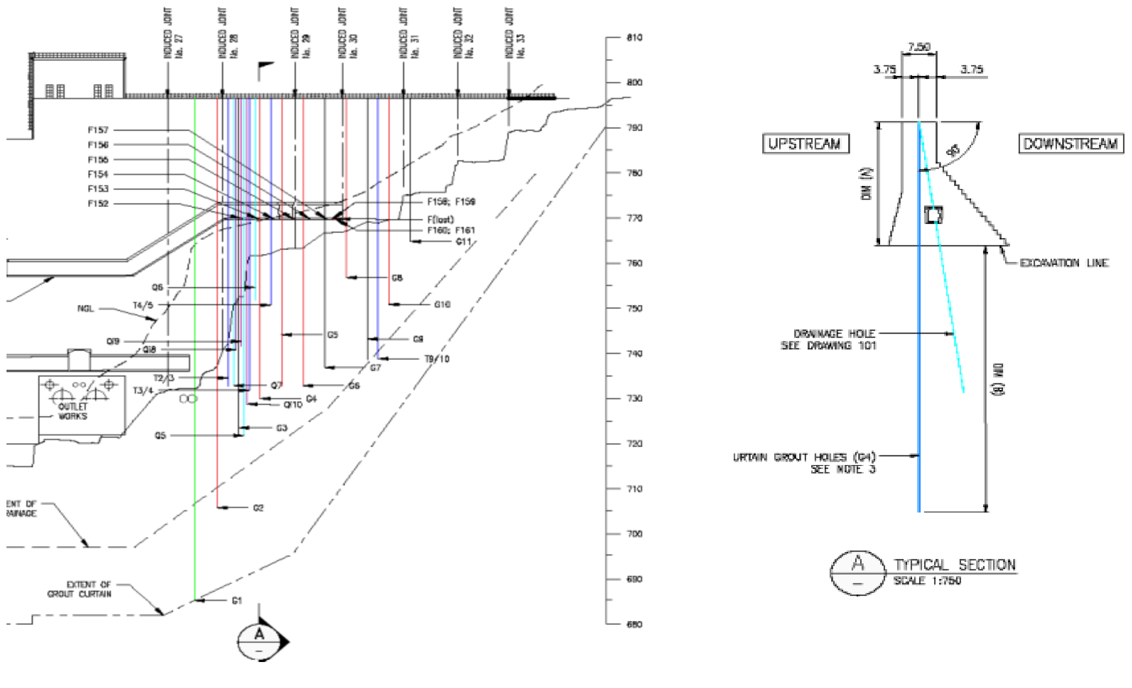

Figure 11. Drilling for grouting (red = primary, black = secondary, blue = tertiary, light blue = quaternary)

Another advantage of core holes, in addition to drilling through the reinforcement, was that the core could be examined to determine where the rock was fractured and/or the dam contact with the foundation was poor.

6.2 *Water Pressure Testing*

Abbreviated water pressure testing and washing of the hole were performed after each stage's drilling or when total water loss was observed during drilling. The abbreviated water pressure test involved three times five-minute tests. Lugeon values were calculated based on the water take, test length and effective pressure in the test section.

The unit water loss in Lugeon units was calculated and recorded by the Contractor and verified by the Engineer for each time interval of the test. The decision to drill deeper and/or drill a splitting hole was largely based on the Lugeon value obtained and/or grout take.

6.3 *Grouting*

Downstage grouting methods were applied, where surface packers were placed at specified depths in the drilled hole. Each grout hole was prepared with flushing and water pressure testing before grouting with a stable grout mixture at a minimum cement-to-water ratio of 1:1. Grouting continued until refusal or when grout takes exceeded 1000 litres. When connections were observed to the drainage gallery's drainage holes during grouting, closed valve mechanical packers were installed in the respective drainage holes to seal them and facilitate the effectiveness of the grouting and were later removed to flush the drainage holes and to measure the seepage flow rate.

Grouting operations were adjusted for large or abnormal grout take, with some stages suspended until the next day for re-grouting. The grouting of any hole or stage of a hole was considered complete when that specific hole refused to take any more grout during the respective 5-minute grouting intervals. The final plugging of completed grout holes was performed after the grouting.

Different grout mixes are used based on grout take, adjusting thickness or allowing temporary setting before re-grouting. A summary of the average lugeon values and grout take per stage for the entire grouting is shown in Figure 12. It provides a summary of the average lugeon value per stage for each grout hole and the average grout take per stage for each grout hole, respectively.

A distinct seepage zone with a moderate to high permeable area was observed from the depth of 25.0 m to the depth of 74.35 m into the rock mass between boreholes T2/3 to G4. The steep foundation interface between T2/3 and G4 can be assumed to be the contributing factor to the high rock mass permeabilities recorded. Moderate permeabilities and grout takes were recorded in the region higher up the left flank (from T4/5 to G11).

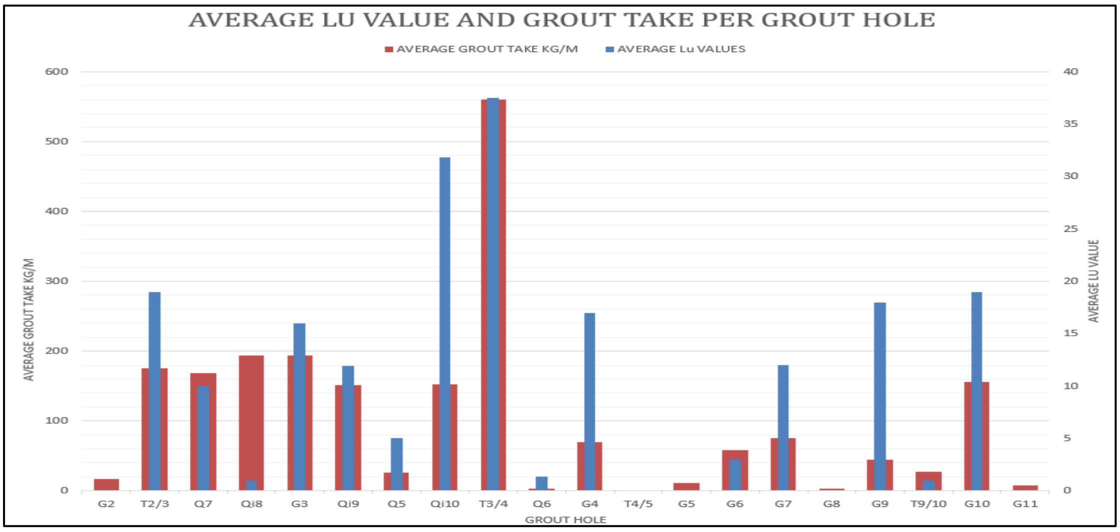

Figure 12. Average Lugeon value and grout take per hole.

6.4 *Challenges Encountered*

The multiple seepage connections to the drilled grout holes posed a challenge to the effectiveness of the grouting operation. The connections were mostly encountered during grout hole drilling, mostly through total water loss of drill water. The following major connections were encountered during the project:

- Left flank upper drainage gallery drainage holes F151, F152 and F153.
- Left flank upper drainage gallery vertical opening at induced Joint 28 (J28).
- Left flank lower drainage gallery F147 and opening at induced Joint 27 (J27).
- Downstream left flank rock face.

7 SEEPAGE MONITORING

Seepage flow measurements of pre- and post-grouting in the upper gallery's left flank were made at VN008 to monitor the effectiveness of the grouting. Table 1 below indicates a significant reduction in flow rate from 10.70 ℓ/s (7 November) to 5.41 ℓ/s (9 December after grouting operations of T3/4 on 10,11 and 14 November, and T2/3, Q5, Q6 and T3/4 on 21 November). The V-notch 8 readings following the grouting of Qi10 on 11 December indicated a reduction in flow rate from 5.41 ℓ/s (9 December) to 2.88 ℓ/s (14 December). The flow rate at V-notch 8 was further reduced to 1.33 ℓ/s on 2 February 2024. This reduction followed the grouting of Qi9 on 22 January. The grouting of Q7 and Qi10 further reduced the flow rate at VN 008 to 1.05 ℓ/s. A flow rate of 1.01 ℓ/s was recorded on V-notch 8 on 24 February. The reduction can be attributed to the grouting of Qi8. The grouting was then terminated after the flow in the left bank gallery had reduced to 1l/s. This clearly indicated a successful grouting operation had been achieved.

07-11-2023	18-11-2023	25-11-2023	12-12-2023	16-01-2024	02-02-2024	17-02-2024	29-02-2024
10.7	7.36	5.33	3.11	1.79	1.33	1.19	1.01

Table 1: V-notch 8 weekly measurements in litres per second

8 CONCLUSIONS

The cause of the sudden increase in seepage between May and October 2021 in the upper left gallery was probably a result of thermal movements in the dam, as this seepage is aligned with the opening of the induced joints on the dam's downstream face. Although this was the likely cause, it cannot be conclusively stated that the increase in seepage may also have resulted from the erosion of some finer material in the rock mass, which caused the seepage to increase and stabilize through a concentrated seepage path. In either case, however, a targeted grouting campaign over the affected area was deemed appropriate to reduce the seepage observed and mitigate further progression of the underlying issue.

The Neckartal dam seepage remedial measures applied at the left flank were successful. The grouting undertaken comprises a single-row grout curtain extending to a maximum drilled and grouted depth of 90.70 m from the non-overspill crest (NOC) surface. A total combined drilled length of 1184 m was drilled, and 37 030 litres (726 cement bags) were injected into the concrete above the foundation interface, rock foundation and rock face.

A highly pervious zone was encountered at the steep slope foundation between T2/3 and G4, which recorded an average permeability of 15 Lugeon and an average cement consumption of 170 kg/m.

Low permeable rock mass conditions were encountered higher up the left flank at the gradually sloping and stepping foundation area, with an average Lugeon value of 5 recorded and a corresponding average grout cement consumption of 43 kg/m.

The flow comparison of pre-and post-grouting of the drainage gallery's left flank indicated a significant reduction in flow rate from 10.70 ℓ/s (pre-grouting flow rate) to 1.01 ℓ/s under FSL conditions.

The seepage through the downstream rock face at the left bank was sealed, indicating an improvement of the overall rock mass permeability that forms part of the abutment. The leak at the downstream face of the wall and at J28 in the upper gallery was sealed as a result of the additional grouting.

It is concluded that the left flank seepage at Neckartal Dam had a multifaceted origin which required varied construction approaches. The systematic and precise sequential grouting procedures using thick, stable cementitious grout gave very satisfactory results. The seepage flow at VN 008 was reduced to about 10% of the pre-grouting flows.

References

1. *A. C. Houlsby. (January 1991). Construction and Design of Cement Grouting: A Guide to Grouting in Rock Foundations.*
2. *Knight Piésold (Pty) Ltd. (March 2021). Neckartal Dam Project: Completion Report.*