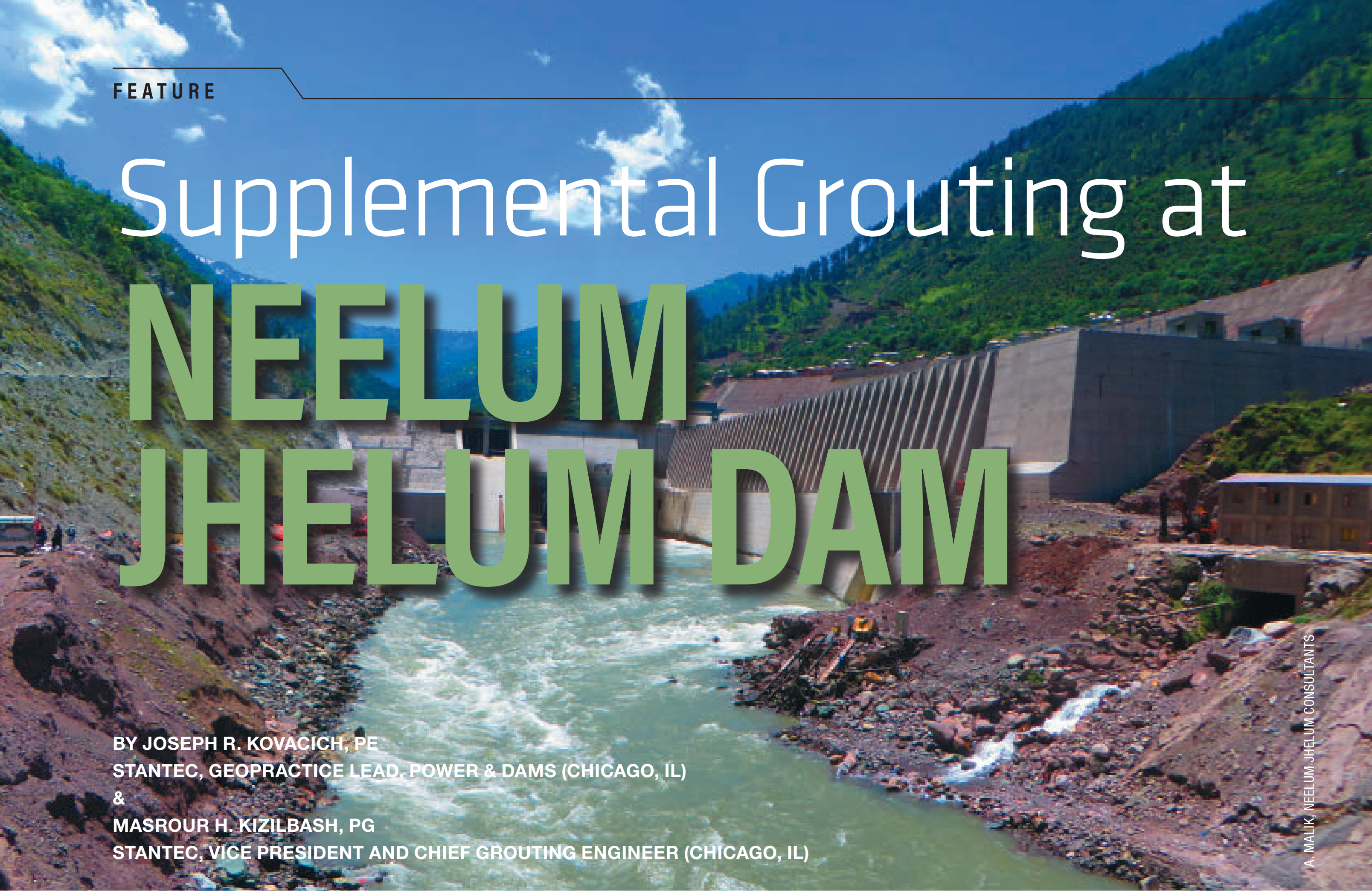

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Supplemental Grouting at NEELUM JHELUM DAM

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The Neelum Jhelum Hydroelectric Project, located near Muzaffarabad in the state of Azad Jammu and Kashmir in northeastern Pakistan, was developed by the Water & Power Development Authority (WAPDA) of Pakistan and has operated since 2018. The project utilizes a gross head of 430 meters by diverting water from the Neelum River using a dam and intake works at Nauseri to the lower branch of the Jhelum River through a 29-km-long tunnel system and underground powerhouse complex with installed generating capacity of 969 MW.

Divided into three construction lots (Figure 1), Lot C2 includes the central headrace tunnel and Lot C3 includes the surge shaft, penstocks, powerhouse complex, and tailrace tunnel. Lot C1, which is the focus here, includes the headworks and the initial section of the headrace tunnel. The headworks (Figure 2) includes a 58-m-high concrete gravity dam with crest at El. 1019 m, a gated spillway, and a gated debris channel. The dam diverts water through the intake, sedimentation basin, and collecting canal and then into the headrace tunnel. Considered active, the Main Boundary Thrust fault (MBT) traces the right riverbank, which necessitated a 54-m-high zoned core rockfill dam (RFD) be constructed over the highly fractured and disturbed rock to accommodate potential fault movements and reduce effects that fault rupture could have on the concrete structures (Dickson et al. 2013; Kovacich et al. 2020).

SEEPAGE OBSERVATIONS

Reservoir impoundment began in October 2017, and the level was raised progressively over several months as project components were completed. By mid-2018 the reservoir reached a level sufficient to commence electricity generation using all four turbines. In July 2018, the reservoir was still being raised toward its full-service level of El. 1015 m and maximum generation.

In late July 2018, 100 mm diameter drains were being drilled in the Debris Channel retaining wall at El. 974 m when significant seepage was reported from some drains. On August 4, 2018, with the reservoir at El. 1006 m, the combined seepage from the drains was estimated to be 2,100 L/min with most of the flow discharging from three of 23 drains: D-14, D-22, and D-23. Though high flows were anticipated initially as the rockfill behind the wall drained, the flows were persistent.

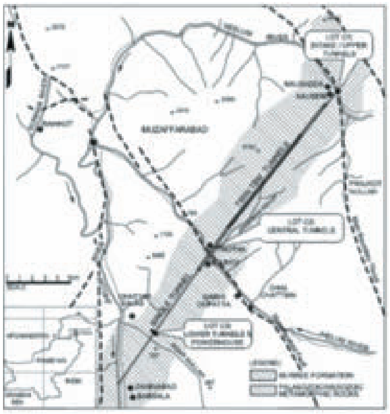
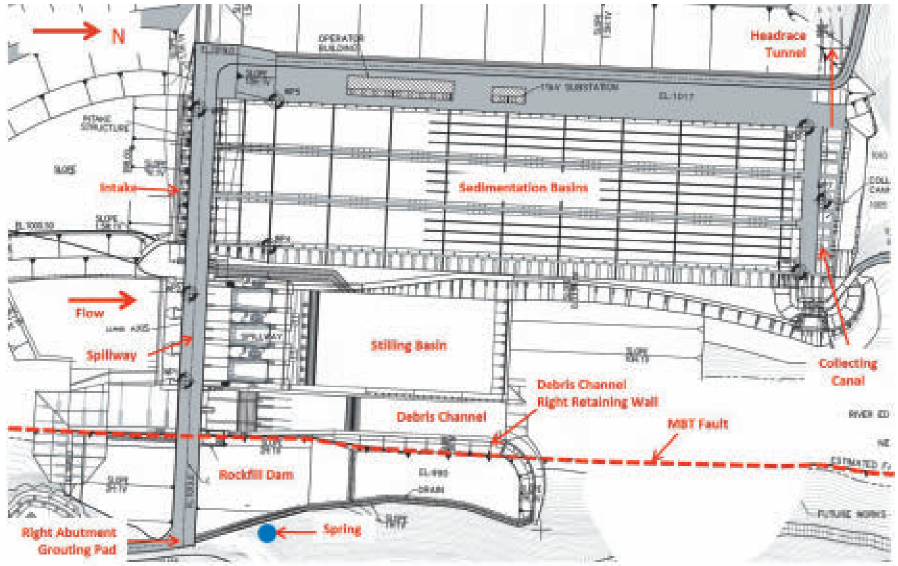


Figure 1 (above): Neelum Jhelum Hydroelectric Project Layout.

Figure 2 (right): Lot C1 Headworks, Spring, and Right Abutment Grouting Area.



On August 15, when the reservoir reached El. 1011 m, a spring was observed on the downstream right bank. Located approximately 45 meters downstream of the dam axis near El. 1005.7 m (Figure 2), seepage was visually estimated to be between 300 and 400 L/min (Figure 3), and the seepage was clear. Flow from wall drains was also greater and flowed from six drains (Figure 4).

On August 17, the Debris Channel gates were opened to flush floating reservoir debris, and during the operation the reservoir was lowered. When the reservoir dropped to El. 1009.7 m the spring dried, confirming strong communication through the abutment. The Engineer recommended to the Owner that the reservoir be held below El. 1009 m until the abutment could be protected.

The following week, the reservoir level fluctuated between El. 1005 m and El. 1008 m. Visual observations of the wall drains confirmed a strong correlation between the reservoir level and seepage (Figure 4), which indicated seepage likely flowed through the right abutment at locations covered by the dam's downstream rockfill shell.

The observations suggested: 1) residual seepage pathways remained in the upper part of the existing grout curtain; 2) seepage from the reservoir was flowing around the existing grout curtain through highly fractured abutment bedrock; or 3) a combination of both. Action was needed to protect the abutment, and the treatment needed to be expedited. Thus, a phased supplemental grouting program was developed to first target the upper abutment, and if needed, the grout curtain could be extended even deeper. The maximum reservoir level would be held near El. 1007 m, allowing two meters of freeboard in the event of upstream flooding or a gate operation error.

Designed as a peaking, run-of-river hydroelectric project, the relatively small

Figure 3: Spring on Downstream Right Bank (left) and Close-up (right).

reservoir is designed to fluctuate daily between El. 1015 m and El. 1008 m. Though the plant can generate with the reservoir as low as El. 1005 m, the net head is less, and the reservoir has very little active storage; thus, daily generation was significantly curtailed. The motivation to reinforce the abutment as soon as possible was obvious to all parties.

INSTRUMENTATION AND MONITORING

Four piezometers were installed in the right abutment as part of the original construction (Figure 5). Vibrating wire piezometer VW-9 is in-line with the grout curtain and set at El. 950 m. VW-10 (not shown) is approximately 30 meters downstream of VW-9 and also set in rock at El. 950 m. VW-26 and VW-27 are approximately 2 meters downstream of the grout curtain and set in the right abutment at El. 990 m and El. 968 m, respectively. To improve coverage during supplemental grouting VW-29, VW-30, and VW-31 were installed downstream of the grout curtains as shown on Figure 5. Data were reviewed daily.

Debris channel wall drain flow measurements were improved by recording the time to fill a 1000 liter tank lowered by crane. To measure the spring flows, the Contractor channelized the flow through a pipe and measured the time to fill a calibrated container. A makeshift v-notch weir was later constructed for more regular and repeatable measurements. Whenever instruments were read, the reservoir level was recorded to improve correlations.

SUPPLEMENTAL GROUTING

The original grout curtain extended to a depth of approximately 70 percent of the reservoir head. When developing supplemental grout hole layouts, the grouting records were reviewed to identify high consumptions zones and to overlap these areas with a new line of holes. Geologic maps of the abutment and the diversion tunnel revealed a low permeable graphite schist that trends upstream-downstream and parallels both the diversion tunnel and the MBT and dips into the abutment. Though weak, the graphite schist, has a relatively low permeability. The concept was to extend the new grout curtain holes deeper and tie-in with the graphite schist.

The supplemental grout hole layout consisted of eight primary and seven secondary holes located along a B-line centered 2.5 meters upstream of the original curtain drilled from a grout pad at El. 1019. In Phase 1 the holes would

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Figure 4: Seepage from Debris Channel Wall Drains.

extend to El. 980 m, and if Phase 2 was needed, the pattern would extend as deep as El. 950 m.

CHALLENGES

Though the work was being expedited, several constraints and challenges had to be overcome. The narrow Athmuqam road, which is critical to Pakistani Kashmir security and is just a few meters above the dam's right abutment could not be disrupted during original construction to facilitate a gallery at that level. Nor was the road wide enough to permit supplemental drilling from it during and keep the road open. The concrete grout pad at El. 1019, which measured approximately 7 m x 7 m, was the only viable space; but the pad only accommodated three drills (Figure 6). The restrictions also meant hole angles were limited.

The Contractor's brute-force and labor-intensive use of single-tube rotary core drills was inefficient, and breakdowns were frequent. Removing and resetting the drill string for each 1.5-meter core run (or less); failing to precisely remeasure drill inclination; drilling angled holes through highly fractured rock; and the lack of tools and hardware to anchor the drills meant holes likely drifted. Poor drilling practices

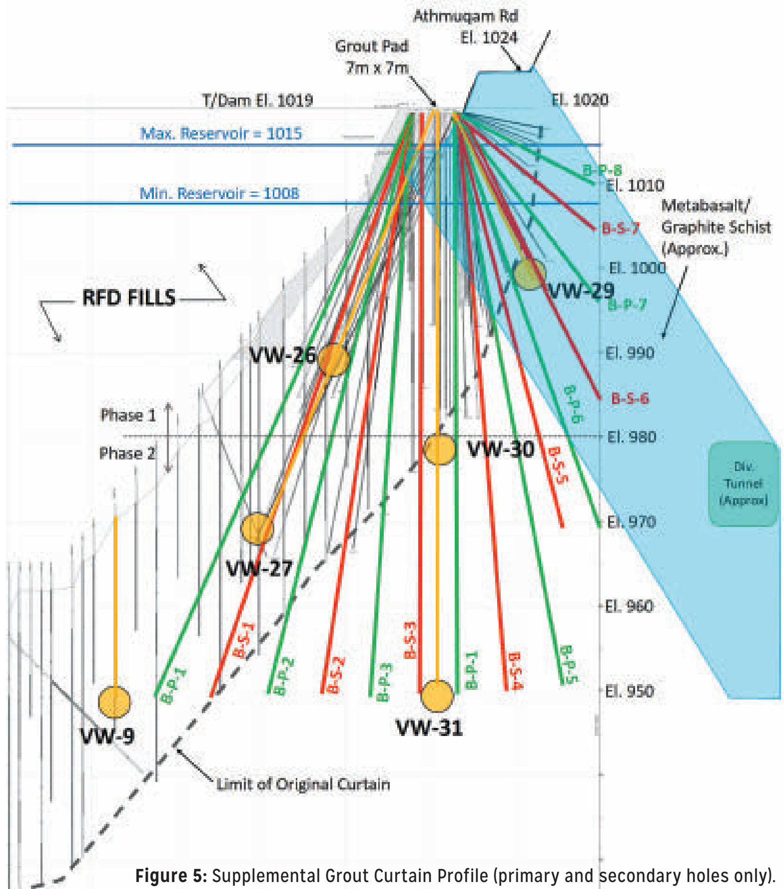

Figure 5: Supplemental Grout Curtain Profile (primary and secondary holes only). Each orange circle is a piezometer tip location.

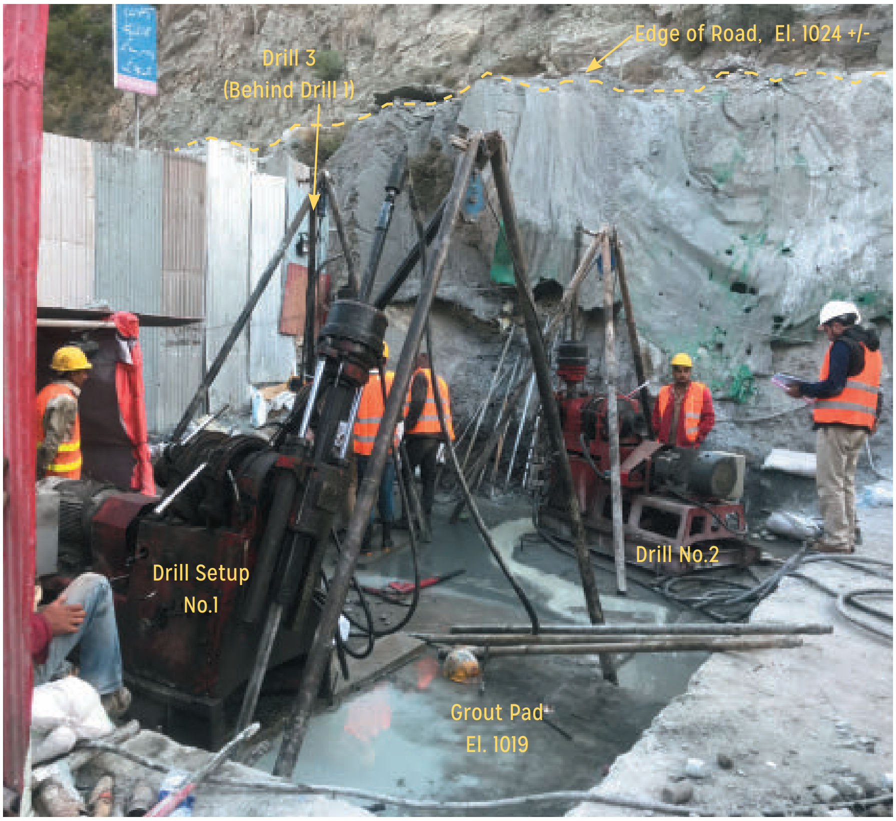

Figure 6: Grout pad at El. 1019 offered approx. 7m x 7m work area.

reduced the team's confidence that holes were all drilled where intended and made it difficult to reliably target specific zones.

With space constrained and low productivity, three additional machines drilled from scaffold platforms were set upstream and downstream of the grout pad in an attempt to improve the likelihood of intercepting the seepage path. Twenty-four holes totaling 510 meters were drilled vertically and inclined 45 degrees into the abutment upstream and downstream of the B-line. Despite injecting 47 tons of cement and 3 tons of sand into these holes there was no appreciable effect. The drills were removed, and efforts were refocused on the B-line.

The Design engineer promoted upstage grouting, where it could, to improve efficiency. However, frequent water losses and repeated hole collapses when the drill string was withdrawn meant downstage grouting became routine.

Stable grout having a 0.5:1 water:cement ratio was the base mix. In some high-take stages, fillers such as sand, sawdust, and bentonite were added. In cases where flowing conditions were suspected, sodium silicate was introduced to reduce the grout setting time from approximately 12 hours to a few hours to reduce washout.

Conventional grouting practice typically dictates that when grout take volume criteria is reached (e.g. 2000 liters of grout) the stage is terminated to reduce grout travel and waste, and split-spaced holes are added. However, drilling rates were typically less than 5 meters/day per drill and slowed by the downstage grouting process and long grout set times. The team found it was more efficient to continue pumping excessive volumes of grout at gravity and low pressures and/or intermittently with the intent of filling open and interconnected joints and voids over a wider area. The approach tended to reduce water losses and high grout takes in deeper stages of holes and adjacent zones. The intent was to extend the width of the grouted zone for each grout hole and thereby reduce the number and amount of time needed for split-spaced holes. Quantifying the benefit of this approach is difficult; however, the cost of wasted or excess grout was easily offset by the generating revenue earned by returning to full service even one day earlier.

GROUTING EFFECTIVENESS

Between September 27 and November 4, 2018, approximately 80 percent of Phase 1 had been completed. Fifty-five tons of cement had been injected and significantly reduced the Debris Channel drain seepage. Continued urging by the Owner to raise the reservoir led the Engineer to develop a grouting effectiveness test.

On November 5, the reservoir was raised from El. 1007 m to El. 1010 m and held for 24 hours. When the reservoir reached approximately El. 1009 m, seepage emerged from the spring, and with the held at El. 1010 m, the seepage from the spring was stable at 160 L/min, and seepage from the Debris Channel drains was approximately 500 L/min, both substantial reductions (Figure 7). The piezometers also showed behavior consistent with a tightened curtain.

Grouting resumed on November 7, but the second and third reservoir cycles confirmed the first cycle behavior. The Phase 1 program was effectively reducing the rock mass permeability above El. 980 m. This increased confidence the seepage could be managed, and the risk of piping and internal erosion was being lessened.

The Engineer also improved operational protocols enabling rapid lowering of the reservoir in the event of an emergency. With greater confidence, the Owner was advised it could slowly raise the reservoir toward El. 1015 m as the remainder of Phase 1 was completed.

By November 17, the reservoir neared El. 1014 m, and seepage from the spring had steadily increased to approximately 480 L/min. During that night shift, 7.6 tons of cement were injected into hole B-P-5 at depth of 25 to 28 meters without reaching refusal. The next day, 3.6 tons of cement were injected in the same stage, again without reaching refusal, so the Contractor elected to move to a new hole. The seepage measurement that day indicated the spring seepage reduced to 420 L/min, a 12 percent reduction, while seepage from the wall drains reduced from approximately 560 L/min to 450 L/min, a 20 percent reduction. The reductions hinted that the B-P-5 stage had intercepted a prominent seepage path. Seepage remained steady until November 26 when the reservoir neared El. 1014.5 m, and the Contractor returned to B-P-5 to resume grouting the 25 to 28 meter

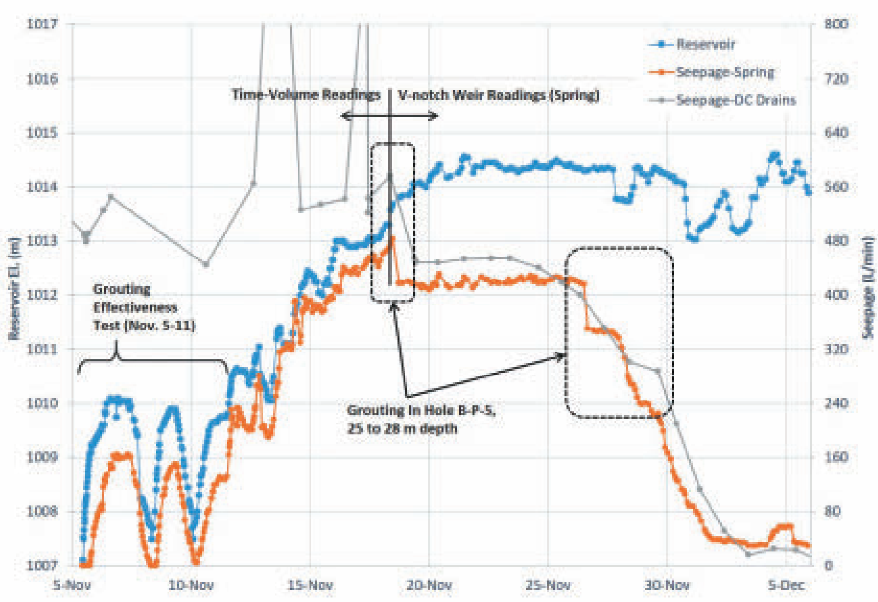

Figure 7: Reservoir and Seepage Data from 5 November to 6 December 2018.

deep stage. After two days of near continuous injection of 20.7 tons of cement, the stage reached refusal.

Seepage from the spring and the wall drains suddenly reduced (Figure 7), indicating a major seepage pathway had been grouted. Additional grouting reinforced this area over the next several days, and by December 2 the spring measured only 30 to 40 L/min. Drain hole seepage had been reduced to 50 L/min by December 2, and all drains were dry by December 7 and remain so today.

With parties satisfied the abutment was protected, the reservoir was near its final level, and the power station was maximizing generation, the Owner determined it would continue with the Phase 2 program to reinforce the curtain. Phase 2 grouting was completed in early January 2019.

GROUTING SUMMARY

Supplemental drilling and grouting started on September 30, 2018 and was completed in early January 2019. As many as six drills and crews worked simultaneously on two shifts seven days a week throughout. Table 1 summarizes the quantities.

To give a sense of the total efforts expended grouting the abutment, nearly 700 tons of cement was injected to consolidate the upper 5 meters of the rock beneath the dam core footprint, which equates to approximately 330 kg of cement per meter of hole. Approximately 628 tons of cement was injected along the original rockfill dam grout curtain, averaging 290 kg of cement per meter drilled.

During supplemental grouting, the average consumption of Phase 1 primary and secondary holes and the holes drilled upstream-downstream of the B-line was 178 kg of cement and 4.9 kg of sand per meter of hole. The average consumption of Phase 1 tertiary and check holes was 101 kg of cement and 0.7 kg of sand per meter of hole, indicating a tighter rock mass after the B-line was completed. Average consumption of Phase 2 holes was 114 kg of cement per meter of hole and 0.6 kg of sand per meter of hole, similar to Phase 1 tertiary and check holes.

Combined, these metrics offer an indication of the poor rock quality that formed the right abutment owing to presence of the MBT fault.

Table 1: Summary of Supplemental Grouting.

Program	No. Holes	Drilled Length (m)	Cement (tons)	Sand (kgs)	Sodium Silicate (kgs)	Saw Dust (kgs)	Bentonite (kgs)
Phase 1 (Prim/Sec.)	15	574	146	2,377	652	37	72
Upstream-Downstream	24	510	47	2,945	114	107	220
Phase 1 Tertiary/Check	9	324	33	225	53	--	--
Phase 2	10	446	51	280	134	--	--
Total	**58**	**1,854**	**277**	**5,827**	**953**	**147**	**292**

LESSONS LEARNED

Excessive seepage necessitated a rapid response to protect the Neelum Jhelum rockfill dam abutment. The experiences gained from this work serves as valuable lessons for future projects.

The Contractor used inefficient and poor quality equipment and a labor intensive 'brute force' approach, which is common in developing countries where modern kits and skilled crews are often lacking. Grouting is a critical dam component and quality should not be sacrificed. Specifications need to require work be performed by qualified contractors equipped with modernized setups and experienced personnel. Shortcomings need to be enforced at the outset. Specialty contractors provide skilled personnel, reliable equipment, materials, tools, institute best practices, and can innovate when challenges necessitate.

The strategic access road and poor quality rock constrained the rockfill dam construction and the supplemental grouting program. Though options here were limited, better access by means of an adit or a slightly widened section of road early in the Project would have allowed more efficient grouting and maintained the road. Providing reliable access during construction and for maintenance should be considered carefully during design development.

All construction projects face schedule pressure. Engineering judgment is required when deciding whether closure criteria at every point along the grout curtain is strictly adhered to, whether localized exceedances can be tolerated, or whether more holes need to be ordered. Ultimately, careful surveillance and monitoring during reservoir impounding is the only way to test the curtain effectiveness. Though supplemental work was necessary at Neelum Jhelum, the observational approach successfully identified the seepage without major consequence.

Foremost, situations involving critical dam safety demand cooperation among the

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stakeholders. Despite past shortcomings, the Contractor mobilized its resources immediately and complied with the Engineer's directions. The Engineer remobilized its expatriate grouting expert and his team to evaluate the situation, and they remained on site throughout the work. The Owner expedited decisions and authorizations. This case, which involve both dam safety and complex site conditions, highlights the need for having highly experienced persons in key management and technical positions to lead the work and who are authorized to make crucial decisions.

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