

DESIGN AND REPAIR OF A POWER INTAKE GATE SEALING SURFACE UNDER CHALLENGING CONSTRAINTS

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ABSTRACT

The 600 MW Shiroro Hydroelectric Power Station began operation in 1990. The plant consists of four 150 MW units each fed by its own 6.3 meter diameter concrete encased steel-lined penstock. The power intake tower consists of four separate bell-mouthed intakes controlled by individual upstream sealing fixed wheel gates. Gate slots are located upstream of each service gate to deploy a separate gate for inspection and maintenance.

During penstock filling of Unit G4 in 2010, the maintenance gate experienced high uplift pressure resulting in jumping (some refer to as catapulting) up and down the gate slot and causing major damage to the second-stage concrete forming the sealing surface along the top of the gate. Approximately 3 cubic meters of concrete broke off and settled in the turbine scroll case. Since access to this area in the dry was not possible, and inspecting with divers was difficult due to the depth of water and lack of visibility, confirming the location and extent of damage was problematic, and subsequent design and repair presented several challenges.

The cause of the problem appears to have been due to a combination of a flow constriction at the bottom of the gate slot and the gate having been raised higher than the prescribed height for penstock filling.

This paper discusses how the damage occurred, how it was investigated, selection of the design solution, and how the damage was eventually repaired.

INTRODUCTION

The Shiroro Hydroelectric Power Station consists of a 125-meter high concrete faced rockfill dam on the Kaduna River in central Nigeria, and a four-unit powerhouse with an installed capacity of 600 MW, making it the second largest hydroelectric project in Nigeria. The 60-meter high intake tower consists of four bell-mouthed intakes, separately serving each unit. Each intake has a 6.8m high x 6.5m wide fixed wheel service gate and

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slots for deploying a maintenance gate 5 meters upstream of each service gate as shown in Figure 1. A single maintenance gate, interchangeable with the service gates, is used for all four units. All gates are designed as upstream sealing gates to eliminate construction of a separate vent shaft, reduce downpull forces and therefore hoist capacity, and allow more frequent dry inspection of the gate members. Each 6.3-meter diameter concrete encased steel penstock is approximately 300 meters in length over a head range of 57 meters.

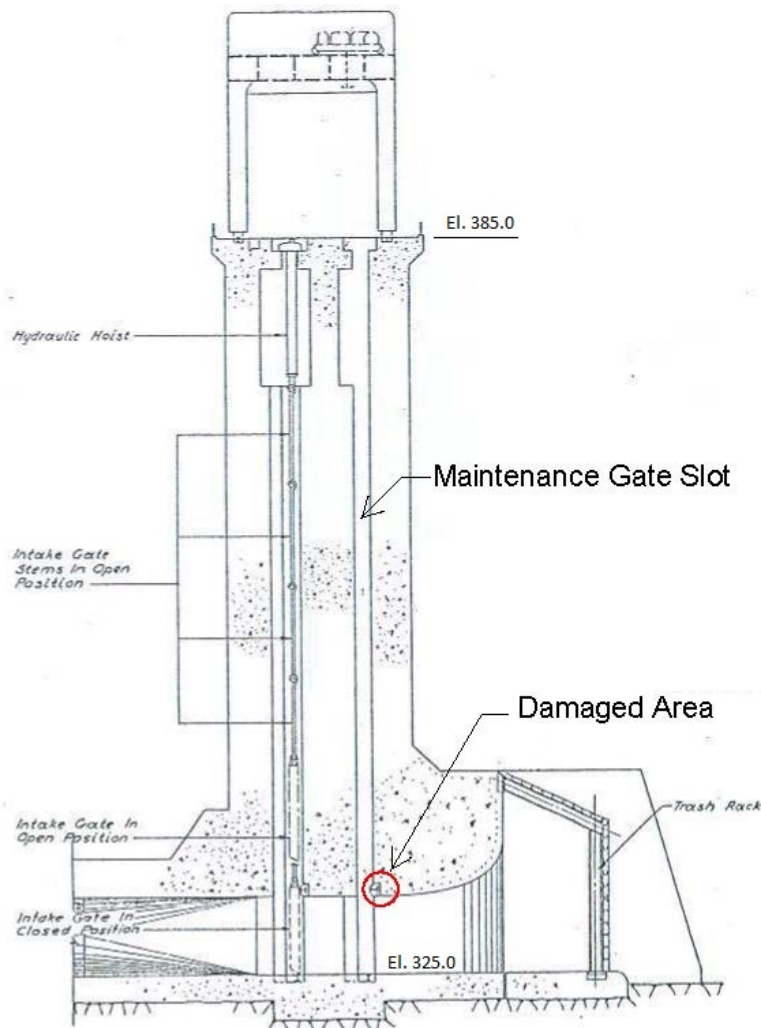


Figure 1. Intake Cross Section

The power station was commissioned in 1990 and is owned by the Government of Nigeria. North South Power Company (NSP) purchased a 30-year concession to operate the power station in 2013 and soon thereafter discovered that the maintenance gate serving unit G4 would not seal.

THE PROBLEM

The following is our best understanding of what occurred based on discussions with people that witnessed the event. During penstock filling sometime in 2010, the maintenance gate serving Unit G4 experienced high uplift pressures resulting in an unexpected jump up the gate slot and back down to the intake floor. This may have occurred multiple times. Banging noises were heard and spray was observed coming out of the gate slot at the crane deck level, El. 385. The service gate was in the closed position during the event, and when noise and spray subsided, operators completed raising the maintenance gate to the full open position. The downstream service gate was then opened to fill the penstock and Unit G4 was brought on line. Though the unusual observations were cause for alarm, there were no immediate indications that there would be any problems with generating power from this unit. Eventually, cooling water filters plugged with sand and concrete aggregate. When this occurred, operators closed both gates to investigate the problem only to discover the maintenance gate had not sealed despite indications it was in the fully closed position. Fortunately, the penstock could be dewatered with the closed service gate allowing the investigation to proceed. Investigators found large pieces of concrete and metal in the scroll case and immediately suspected it to be part of the maintenance gate slot. The original lintel seal plate retrieved from the scroll case is shown in Figure 2.



Figure 2. Lintel Seal Plate with Concrete Removed

The maintenance gate shown in Figure 3 was raised to the top of the intake tower and was found to have also experienced damage. The gate was subsequently repaired for use with the three other units, however the damage to the Unit G4 gate slot prevented using it there. Due to annual reservoir fluctuations, the damaged portion of the gate slot was under 30 to 55 meters of zero visibility water year-round, which complicated assessing the damage.



Figure 3. Downstream Side of Maintenance Gate Following Repair

INVESTIGATING THE PROBLEM

NSP had physical evidence that damage to the intake had occurred but the exact location and full extent of damage would not be known until the suspected area could be visually examined. NSP hired Tetra Tech in 2014 to investigate the cause and extent of the damage and determine how to repair it. Interviews with the power station engineers confirmed that the damage was likely caused by the 2010 event, and the dimensions and visual observations of materials recovered closely matched the gate lintel. It was not known what else may have been damaged but remained intact.

Being the furthest upstream gate slot, the damaged slot could not be easily dewatered for dry inspection, and extremely turbid water year-round made it also difficult to obtain underwater photographs, video and measurements. The use of aluminum sulfate to provide temporary underwater visibility for a diver was considered, but was not effective in early trials. It was concluded that the inspection would need to be performed underwater with precision measurements to understand the full extent of damage. The technique chosen was side-scan sonar imaging. With imaging, turbid water is not a factor, three-dimensional digital measurements are determined and the safety risk is eliminated.

The location and extent of damage was determined by comparing the scanned image of the damaged intake area of Unit G4 with the scanned image of the undamaged identical intake area for Unit G1. By comparing the difference between these two sonar scans a graphic of the damage to the gate slot could be visualized, as shown in Figure 4. The color zones represent the amount of lost material from yellow (200mm) to dark blue (650mm).

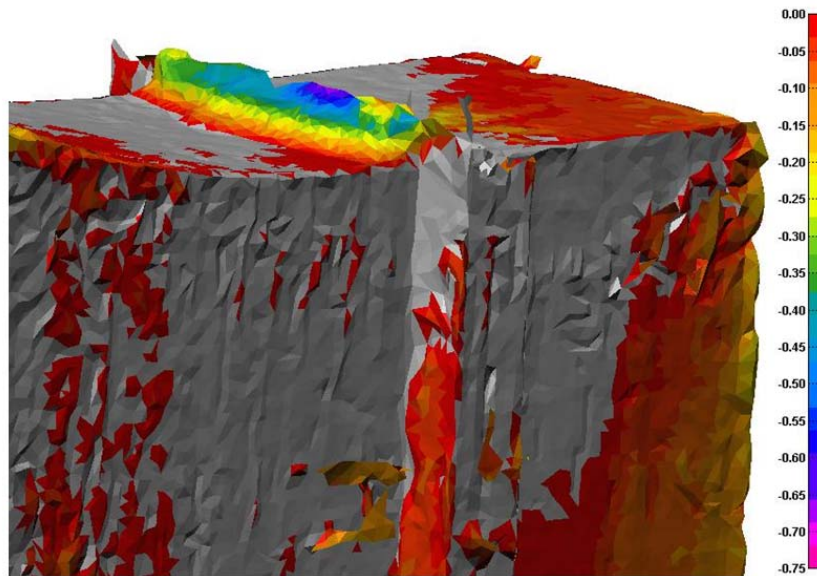


Figure 4. Sonar Scan Showing Extent of Damage to Unit 4 Intake Slot (Units in Meters)

Comparing measurements taken from the sonar scans, and visual observations of the recovered concrete and metal materials, confirmed that the damage was confined to the lintel.

SUSPECTED CAUSE

The occurrence of upstream sealing gates jumping, or “catapulting”, violently upward in their gate slots is a known but somewhat rare phenomenon. Similar events have been documented at Dworshak Dam and Mossyrock Dam¹, and the U.S. Army Corps of Engineers has conducted hydraulic model investigations of this issue at Big Bend, Stockton, Harry S. Truman and Clarence Cannon Dams². The observations and information obtained at Shiroro Dam are consistent with these previously documented events and analysis.

Penstock filling at Shiroro Dam is accomplished by raising the service gate 150mm until the penstock is completely filled and balanced pressure across the gate is achieved. The vent area downstream of the service gates is larger than the area downstream of the maintenance gates. This allows for quicker filling time for the service gates than for the maintenance gates. When a maintenance gate is in the closed position, the specified

process of penstock filling begins with lowering the downstream service gate to the closed position. The small volume between the two gates is then filled by raising the maintenance gate 150mm until balanced pressure is achieved. After pressure is balanced the maintenance gate is raised to a storage position out of the waterway. The service gate is then raised 150mm until the penstock is filled and balanced pressure achieved.

The Shiroro intake gates use an upstream sealing design with a relatively narrow vent opening on the downstream side. Based on fabricator’s drawings there is a 131mm gap between the maintenance gate slot’s downstream concrete face and the downstream face of the gate as shown on Figure 5. The gap area has been referred by others as the “back-of-gate orifice”. Once the water level rises to the crown of the penstock the only outlet for penstock fill water is upward through the gate shaft through the gap, acting as an orifice, between the gate and the shaft wall. If this area is less than the area of the inlet orifice created by slightly raising the gate, then the risk of developing a spike in uplift pressure is increased. Since operating procedures specify cracking the gate open 150mm to fill the penstock, conditions were in place to temporarily develop high uplift on the gate. Add to this the fact that the means to raise the gate are not precise making it possible that the gate was raised higher than 150mm thereby increasing the probability and magnitude of developing adversely high uplift.

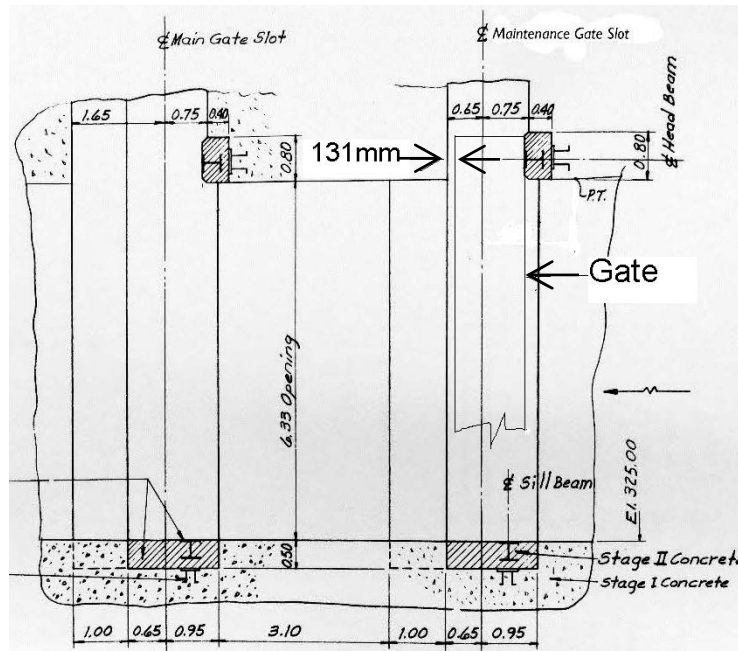


Figure 5. Maintenance Gate Slot and Gap Dimensions

The diagrams in Figure 6 illustrate the progression of gate movement through the gate jumping process.

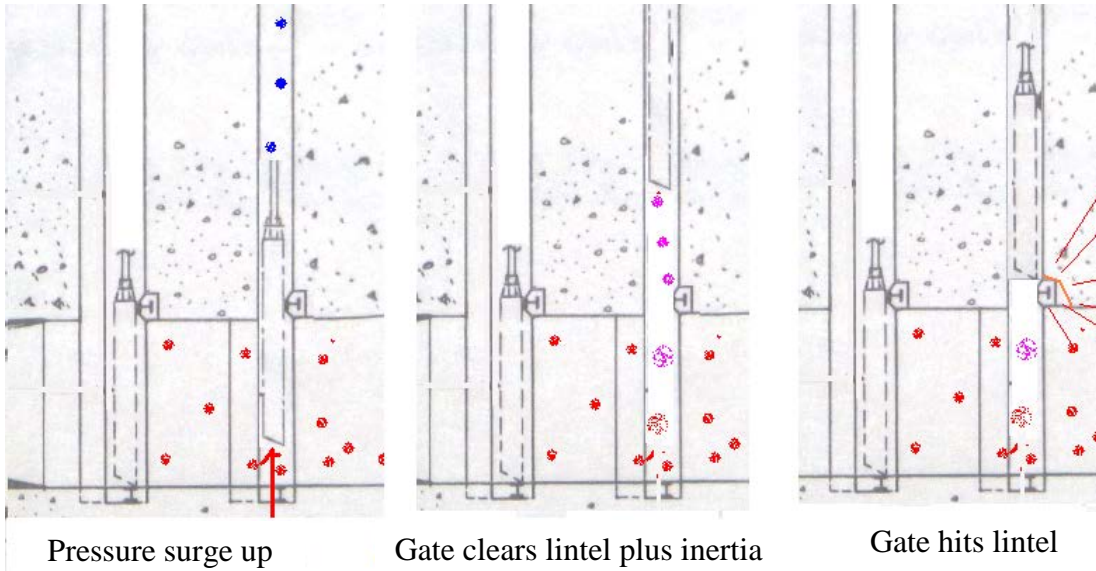


Figure 6. Sequence of Gate Jumping

DESIGN SOLUTIONS

The first decision was whether to attempt the repair in the wet or to dewater the maintenance gate slot before repairing it, however both options faced a number of challenges. Due to sealing characteristics of upstream gate seals the maintenance gate would require that the lintel be repaired within a few millimeters of its original position, which would be difficult to accomplish under the high head with near zero visibility. After weighing all the risks, it was decided not to attempt to repair the lintel in the wet, but instead develop a solution that allows for repair in the dry. However, dewatering the intake to perform the repair in the dry faced a number of challenges as well.

The first challenge was that the maintenance gate slot was designed to be the upstream-most closure in the system and there were no stoplog slots in place, therefore custom-made steel bulkheads would need to be installed across the bell-mouthed intake to seal it and allow dewatering. However the bell mouthed intake did not provide flat surfaces for a bulkhead to bear against during dewatering, requiring that the bulkhead seal against the curved surfaces, as shown in Figure 7 below.

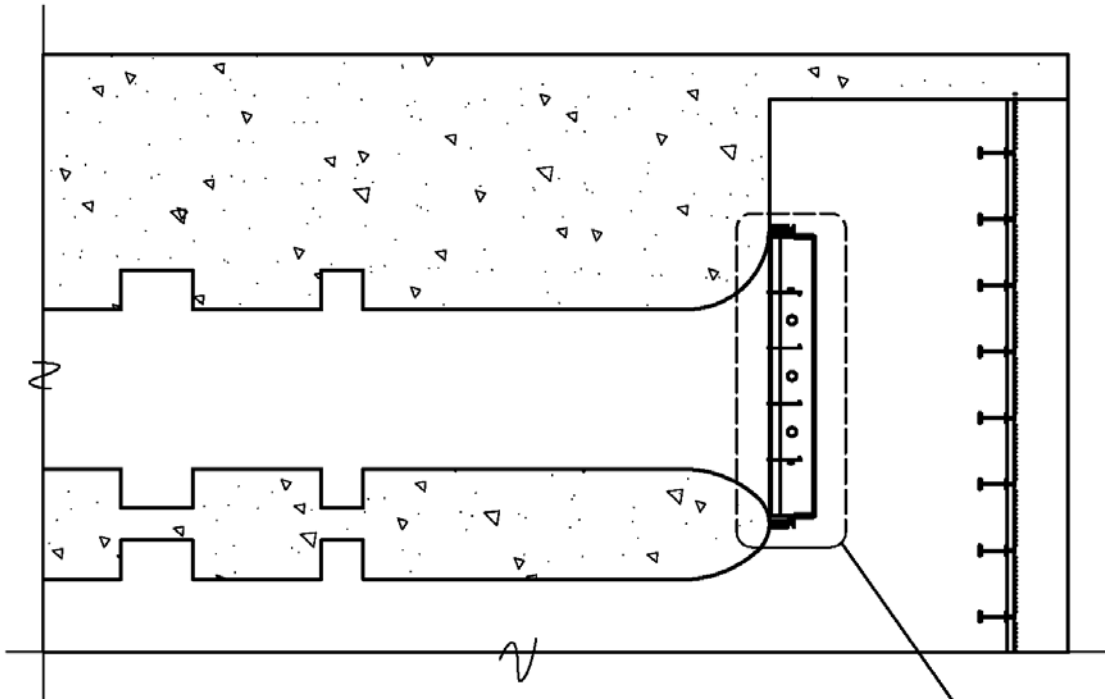


Figure 7. Plan View of Bulkhead Installation over the Intake

The second challenge was that the access bridge to the intake tower could not safely carry the 50-ton weight of the bulkhead. The entire bulkhead would need to be 9.3m wide x 10.7m high to fit over the upstream side of the intake. The weight problem was solved by designing the bulkhead in five horizontal segments, which could then be barged to the intake and stacked in place. Barge cranes were not available so this was accomplished by floating each stoplog segment with airbags and towing to the intake with small boats.

The third challenge was getting the bulkhead through the robust trashrack structure in place over the intake. This was accomplished by reinforcing the structural frame of the trashrack with a temporary brace, then cutting an opening in the top to permit the bulkhead segments to be lowered into place. After the bulkheads were removed, the structural frame was repaired using bolted splice plates.

The bulkhead design was made up of five bulkhead segments weighing approximately 10 tons each, which could be lowered into position on the face of the intake and stacked in place. While the water depth was not expected to exceed approximately 40 meters during the planned work, the bulkhead was designed for the maximum water depth of 60 meters at any time during the year to protect against the possibility that construction delays would force it to stay in place during the wet season.

Rubber “J” seals at the sides of each bulkhead segment sealed against the curved face of the concrete intake structure and wiper seals connected each segment to each other. Accurate alignment of the segments was critical for them to provide a watertight seal, therefore steel guide rails were initially installed to help guide the stoplogs into the

correct position. Finally, a 150mm ball valve was installed on the top bulkhead to allow the penstock to be filled again after the lintel repair was complete. A basic picture of the stoplog design is shown in Figure 8.

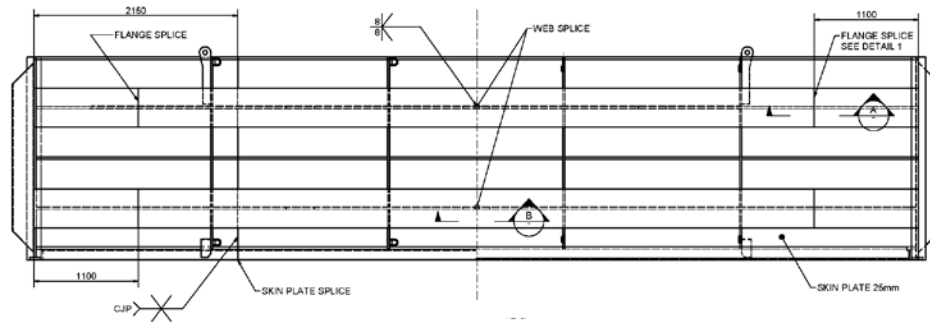


Figure 8. Elevation View of Typical Stoplog Segment

The design of the lintel repair was comparatively simple. The sonar scanning data showed that the existing lintel beam would need to be replaced, and that damage to the side seal plates was limited to the top meter of length. A new stainless steel lintel and side seals were designed to match the existing geometry. These would be lowered into place and attached to the face with concrete anchors, then serve as a form to place concrete, as shown in Figure 9.

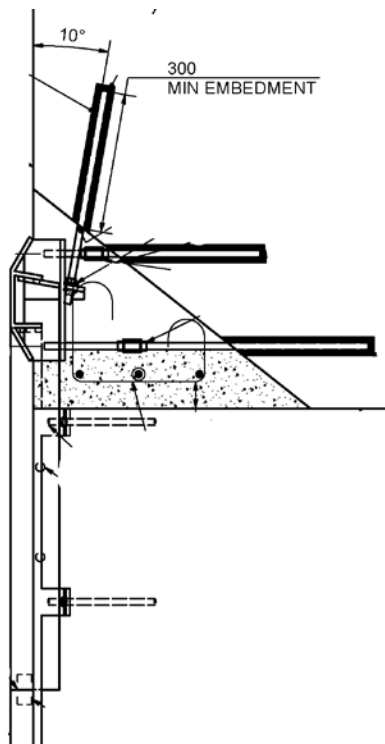


Figure 9. Repaired Lintel and Side Seals

CONSTRUCTION

Timing was critical. The reservoir level is typically at around El. 360 between April and June then steadily rises to around El. 382 by September. The increase in reservoir level severely reduced the amount of dive time for an individual diver, thereby increasing the number of divers needed to accomplish the work.

The bulkheads were fabricated on site due to the additional time and cost that would have been required in transporting them to the site from Lagos or elsewhere. A Nigerian contractor was selected to fabricate the five bulkhead segments. Shop machinery and tools normally present in steel fabrication shops were not available. The work was performed by torch cutting 25mm steel plates and welding the assembled pieces together in an open bay inside the powerhouse. This process resulted in rough edges that varied by as much as 20mm, which is greater than the tolerance that would result from work in a metal shop. This caused some concern since the bulkheads had to stack precisely with the ends bearing against a curved surface, and the divers had to do this largely by feel due to the lack of visibility. After some adjustment, a fit up test was performed by stacking the bulkhead segments in the powerhouse, as shown in Figure 10.



Figure 10. Fit-Up Test of Two Bulkhead Segments

The bulkheads were installed by an American contractor with experience in underwater construction at hydroelectric projects. The presence of crocodiles at the surface contributed to constructability concerns, but overall only a couple were ever sighted during the construction activity. A winch assembly was attached to the intake tower to allow the

bulkheads to be lifted and lowered during installation and removal. Next, openings were cut in the trashrack and the temporary bracing was installed. Then the guiderails were installed on the face of the intake using an alignment frame. During the installation of the guiderails, it was discovered that the upstream face of the intake was a different shape than was shown on the design drawings, requiring that they be modified to sit at a wider angle than planned.

After the guiderails were in place, the bulkhead segments were installed. This was accomplished by attaching air bags to them and floating them to the intake from a nearby boat launch, then lowering them into position using the winches. After all five bulkhead segments were in place, an attempt was made to dewater the intake using the service gate to control the water flow, however the leakage rate was too great to proceed. An inspection by the construction divers determined that the guiderails were preventing the bulkhead segments from seating against the face of the intake and would have to be removed.

Once the guiderail was removed the bulkhead segments were reinstalled on the intake. Without the guide rail in place, the bulkhead was aligned manually, then attached to the face of the intake using chain come-alongs attached to the concrete face. Leakage was initially unmanageable, however after the installation of additional rubber seals between the bulkhead segments, the leakage reduced to a steady but manageable spray.

The lintel repair was completed by a Chinese contractor working on other hydroelectric projects in the area. Scaffolding was constructed inside the intake, as shown in Figure 11, to reach the 6 meter height and keep workers above the bulkhead leakage flowing along the invert. Next, the damaged side seal plates were cut off and the new lintel and side seal plates were installed using concrete anchors. Finally, concrete was placed to complete the repair.



Figure 11. Preparing for Repair of the Damaged Lintel

The first test of the maintenance gate was performed three days after concrete placement and the leakage rate was minimal. When it was determined the lintel repair was successful the trashrack panels and beams that were initially removed to install the bulkheads were reinstalled and coated where bare metal had been exposed. Work was completed in July 2016.

CONCLUSION

There are several lessons for owners and engineers who are confronted with a similar problem.

- Upstream sealing gates must be operated cautiously to prevent creating the kind of high uplift pressures that caused the damage at Shiroro Dam.
- A modern scanning sonar system is powerful. It can provide engineers with a three-dimensional model of underwater features which they cannot see and allow them to take whatever measurements they need during design. On this project, the sonar scan took engineers from suspecting that the lintel was damaged to knowing the extent of the damage, with all the dimensions they needed to design the repair.
- Bulkheads can be designed to seal against a rounded intake that was not designed for them, as long as they are designed to match the side slopes of the face and are installed in the correct alignment.

ACKNOWLEDGEMENTS

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