KLAMATH RIVER RENEWAL PROJECT - DESIGN OF DAM MODIFICATION FOR RESERVOIR DRAWDOWN, RIVER DIVERSION AND DAM REMOVAL OF THE COPCO NO. 1 DAM

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ABSTRACT

The Copco No. 1 Dam, a former dam on the Klamath River in California, was removed in 2024. The 38.4 m high concrete arch-gravity dam with a gated overflow spillway retained a 50 million m^3 reservoir. Reservoir drawdown and temporary river diversion were required to evacuate the reservoir, release accumulated sediment and to allow removal of the concrete dam and foundation below the original river grade.

The pre drawdown activities required the construction of a new low-level outlet consisting of a 3.2 m D-shaped tunnel section with an outlet conduit and reopening of the existing diversion tunnel. The outlet works were sized to provide sufficient discharge capacity to evacuate the reservoir and divert the river in conditions up to the 5% probable monthly flood. The pre drawdown work was completed while the hydroelectric facility was in operation.

The design phase and construction of the Project required evaluation of various reservoir outlet alternative layouts. The selection of the preferred arrangement was made based on reducing construction costs and schedule risks.

RÉSUMÉ

Le barrage Copco No. 1 est un ancien barrage sur la rivière Klamath en Californie qui a été démantelé en 2024. Le réservoir, dont la capacité était de 50 millions de m^3, était retenu par un barrage poids-voûte en béton d'une hauteur de 38,4 m. L'abaissement du niveau du réservoir et la dérivation temporaire de la rivière étaient nécessaires pour permettre l'évacuation des sédiments accumulés, le démantèlement du barrage en béton et l'excavation de la fondation en béton sous le niveau de la rivière.

Les travaux de préparation de projet comprenaient la construction d'un nouvel évacuateur de fond composé d'un tunnel de section en forme de D de 3,2 m avec une conduite de sortie, et la réhabilitation du tunnel de dérivation. Les travaux ont dû être exécutés pendant l'opération de l'aménagement hydroélectrique. L'évacuateur de fond a été conçu de manière à avoir la capacité de débit requise pour les différentes phases de l'évacuation du réservoir.

Le succès de la phase de conception et construction du projet a nécessité l'évaluation de plusieurs scénarios sur les ouvrages d'évacuation de réservoir envisageables. La sélection de l'aménagement a été basée sur le scénario présentant le moins de risques, en tenant compte du prix et des impacts potentiels sur le projet.

1 GENERAL

The Copco No. 1 Dam was built between 1911 and 1922. Located on the Klamath River in Siskiyou County, California, the dam is one of four dams and hydroelectric facilities owned and operated by PacifiCorp which were removed in 2023 and 2024 as part of the Klamath River Renewal Project. The Klamath River Renewal Project is described in Nistor et al. (2025). The dam and reservoir are shown in Figure 1.

The Copco No. 1 facility was comprised of the following major components:

- A reservoir, also called Copco Lake, with approximately 50 million m^3 of storage.
- A concrete gravity-arch dam, founded on bedrock, with the crest approximately 38.4 m above the downstream river level.
- A 13-bay ogee crest spillway with radial (tainter) gates.
- A diversion tunnel that was permanently blocked with a concrete plug, located on the left abutment.
- The power intake, penstocks and powerhouse on the right abutment.
- Two turbine-generators with a total installed capacity of 20 MW.

Figure 1: Aerial photograph showing the Copco No. 1 Dam and Copco reservoir. (Credit: KRRC)

2 DAM REMOVAL

As part of the Project, the Copco No. 1 facility was selected for decommissioning and full dam removal. Conceptual designs for the dam removal were developed by several parties to support National Environmental Policy Act (NEPA) and Federal Energy Regulatory Commission (FERC) permitting of the

Project. With these designs and permit applications, key design criteria for the final design were developed, including the following:

- The US Bureau of Reclamation (USBR, 2011) completed hydrology, hydraulics, and sediment transport studies on the effects of sediment mobilization and evacuation during the reservoir drawdown. The dam notching method and the low-level outlet method were evaluated. Reservoir drawdown via a low-level outlet was selected to reduce downstream flood risks and increase sediment mobilization during the drawdown period.
- The reservoir drawdown period was specified to be within January through September of the drawdown year to reduce downstream aquatic and biological impacts.

Knight Piésold (KP) considered the previous design concepts and regulatory constraints in its development of construction designs for Kiewit Infrastructure West Co. (Kiewit). The construction designs are reported in KP (2022) and described in this paper.

3 RESERVOIR DRAWDOWN

Design of the pre-drawdown works involved consideration of the following critical constraints:

- Early engineering studies developed by the Owner involved the use of the existing diversion tunnel for reservoir drawdown. Limited construction drawing, as-built survey or operational data was available. This was considered to represent significant uncertainty for the operation of a pressure tunnel.
- The facility's power intake would only allow drawing down the reservoir to some 5 m below the normal maximum reservoir level due to the invert level of the intakes.
- The reservoir had to be fully drawn down during the winter season (January through March) to meet environmental objectives regarding sediment flushing.

3.1 Design Development for Drawdown Outlet

Several alternative layouts for the primary reservoir drawdown outlet were developed to meet the same constraints and considerations as those which were considered for the permitting and development of design criteria for the Project. The alternatives were evaluated to ensure technical feasibility, ease of construction, and costs and schedule risks.

The alternatives evaluated are described below.

3.1.1 Existing Diversion Tunnel for Reservoir Drawdown

The first alternative evaluated for the primary drawdown outlet is to make use of the rehabilitated existing diversion tunnel to drawdown the reservoir. The existing diversion tunnel is a 4.9 m-wide by 5.5 m-high rectangular shaped tunnel constructed by drill-and-blast in rock. It was equipped with three 1.8 m diameter control valves and a concrete structure located at the inlet portal. Previous attempts at investigation of the submerged headworks were limited to bathymetry, and investigation by remote operated vehicle to locate the submerged equipment were unsuccessful in obtaining clear images due to the opacity of the water.

This alternative would require removing the 5 m thick concrete plug and approximately 8 m thick concrete inlet structure, both exposed to the reservoir's hydrostatic pressure, the construction of a tunnel concrete transition and new outlet gate and removal of the submerged concrete headwork. For this alternative the outlet gate is required to allow construction work to be completed in advance of the drawdown period and provide flow control during the reservoir drawdown. The energy dissipation method required for this alternative was not developed in detail.

While this concept afforded the advantage of utilizing an existing facility for drawdown operations, this alternative was rejected based on the construction risks due to the required underwater work and longer schedule to fabricate and put in place the control gate and concrete transition.

3.1.2 New Low-Level Outlet for Reservoir Drawdown

This alternative requires the construction of a new low-level outlet structure sized to draw down the reservoir. The new outlet is an inclined tunnel section through the base of the concrete dam – it includes a cast-in-place concrete transition from the drill-and-blasted tunnel to a steel outlet pipe to direct flows to the existing spillway plunge pool directly upstream of the powerhouse. The low-level outlet would be opened at the time of initiation of the reservoir drawdown by the lake tap method. Through the lake tap method, tunnel excavation is advanced from the dry downstream side up to a final tunnel round (plug). At the time of drawdown, the final tunnel round, exposed to the full reservoir hydrostatic pressure on the upstream side, is blasted to allow the release of flow.

This alternative was selected to be designed for the Project. The Project risk and schedule profiles were more favorable compared to the alternative above.

The existing diversion tunnel would be reopened by excavating the submerged 8 m thick concrete inlet structure and removing the existing 5 m thick concrete plug by lake tap to complete the temporary diversion of the river.

A design variant with two-separate outlet tunnels was considered to provide increase discharge capacity in flood conditions. This variant was decided by the Project team to not be required.

3.3 New Low-Level Outlet Configuration

The new low-level outlet was located above the historic river channel grade, in an area of the dam that formed the upstream cutoff wall during construction. The outlet is a 54.1-m long, 3.2 m high by 3.2 m wide unlined D-shaped tunnel section at a uniform downslope grade of 9%. The tunnel transitions to a 30-m long, 3 m diameter steel pipe discharging in the existing stepped spillway plunge pool. Erodible material of the river channel at the plunge pool was already removed by historic operation of the existing stepped spillway. Minimal erosion damage from the drawdown discharge was expected.

Bathymetry and historic photos indicated the inlet channels to the diversion tunnel and new outlet had accumulated sediment and potentially construction waste including excavation debris and large timber. The inlet channels were mechanically dredged in advance of the reservoir drawdown to ensure that no blockage or flow restriction would occur when opening the outlet tunnel plug. This required mobilization of dredge equipment and barges inland to the reservoir. A local recreational marina was used to launch the equipment.

The steel pipe allowed an access track to be constructed to the base of the dam to allow the removed dam material to be hauled to the designated on-site disposal area. The protection embankment was designed to allow concrete rubble to be pushed down the spillway without damaging the outlet. Concreted riprap protection was provided to limit damage from the potential spillway discharge in flood conditions and from backflow caused by the outlet discharge. Removed dam material was be hauled to a near-by on-site disposal area. The outlet protection embankment is shown in Figure 2.

Additionally, modified reservoir operation was put in place to operate the reservoir at the Normal Minimum Reservoir Operation level. This would provide some storage in reservoir to attenuate floods.

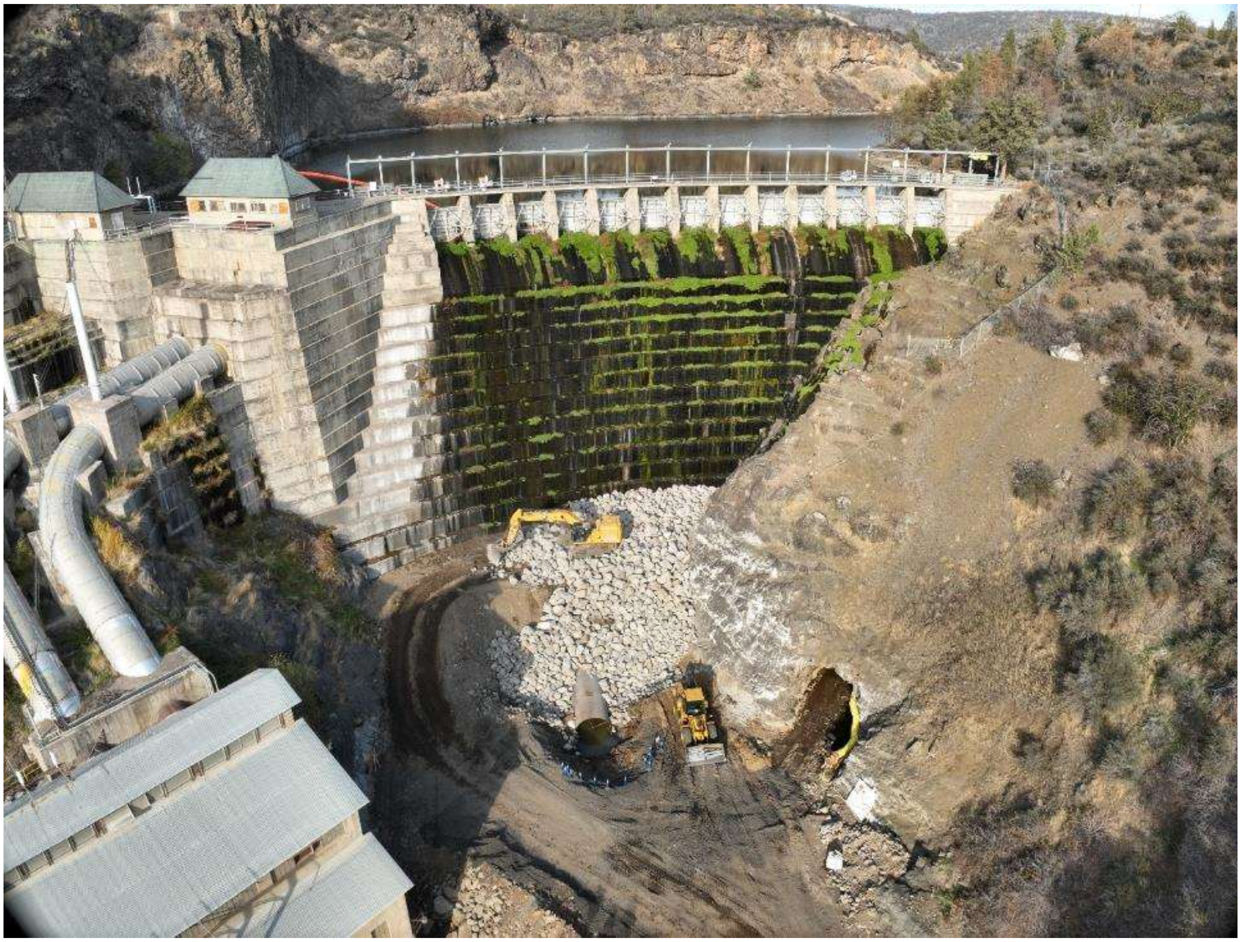

Figure 2: Construction of the Low-Level Outlet Protection Embankment. (Credit: Kiewit)

3.3.1 Tunnel and Plug

A 3.6 m diameter thick plug exposed to the reservoir hydrostatic pressure was left in place, drilled with 100 drill holes, 3-m-long required to prepare the final plug removal. The plug although drilled, was left for five months to retain the reservoir under its operating level during the pre-drawdown period. The plug structural strength was analysed based on the allowable tensile stress and allowable shear stress of plain concrete, following the provisions of ACI 318 Building Code Requirements for Structural Concrete.

Steel railroad rails and joint keys were used during construction in 1911 to ensure interlocking construction joints throughout the concrete placement during construction of the dam. The concrete strength was not tested, however, based on the concrete mix proportions reported on the construction documents conservative assumptions for the concrete properties could be made based on the cement content. The drill and blast excavation were optimized to ensure limited overbreak and ensure the randomly embedded railroad rails would not affect advancement of the tunnel. The plug showed only minor signs of water leakage from the reservoir, which could be sealed by grout. Water resistant explosives and detonating devices were installed at the beginning of January. The plug was successfully blasted, with the inlet cross-section required for the opening met.

The Low-Level outlet operated between January to March of the Drawdown year (2024).

3.3 Temporary Diversion

The existing diversion tunnel was used for the temporary river diversion when the discharge capacity of the low-level outlet was no longer sufficient to lower the reservoir level due to the river inflows. Reopening the existing diversion tunnel required access on the left abutment of the concrete dam to excavate and remove the abandoned concrete headwork structure and tunnel plug. The work was completed by winch-assisted excavator to lower the equipment on the steep embankment slope. The concrete was demolished with a hydraulic hammer.

During the temporary diversion earthfill dikes were required to dewater sections of the foundation to allow removal to a depth below the design river channel grade.

The diversion tunnel operated between March to September of the Drawdown year (2024), as shown in Figure 3. At completion of the dam removal works and reconstruction of the river channel, the inlet and outlet diversion tunnel portal were blocked with earthfill embankments.

Figure 3: Concrete excavation for dam removal. Klamath River is diverted through the diversion tunnel. (Credit: Kiewit)

4.0 HYDRAULIC STUDIES

Design of the outlet works required detailed hydraulic studies to be completed to develop the structures arrangement and determine hydraulic performance for the full range of reservoir level, from submerged orifice inlet control to open channel condition.

4.1 Computational Fluid Dynamics Analyses

One-dimensional hydraulic computations used throughout the design phases were validated and supplemented by Computational Fluid Dynamics (CFD) analysis. Two three-dimensional (3D) models were developed with Flow-3D (Flow Science Inc.) and Fluent (Ansys, Inc.) to investigate the following:

- Discharge and flow characteristics
- Air flow requirement
- Potential for vortex formation at the inlet
- Evaluation of cavitation potential
- Energy dissipation in the downstream river channel

The modeled boundary included a section upstream of the reservoir, the dam, the low-level outlet and a section of the downstream river channel.

Simulations were completed for key reservoir levels.

The CFD analyses were used to confirm the specified reservoir level at which the diversion tunnel could be opened was set. This reservoir level was selected to limit the exposure of the low-level outlet to vortex action which could entrain floating debris and reduce discharge. The analyses also indicated that larger sediment or boulders would not be mobilized as flow velocity in the reservoir remains less that 1.2 m/s during the drawdown and temporary diversion phases.

4.2 Operating Conditions

The low-level outlet was designed with a maximum discharge capacity of approximately 120 m^3/s at the Normal Maximum Reservoir Operating level. High-velocity flow, in excess of 24 m/s within the outlet were dissipated quickly within the river channel. Simulation of water pressure on the outlet water passage at the maximum discharge indicated no negative pressures for all discharge conditions and no potential for cavitation damage and erosion of the concrete surfaces. A 900 mm diameter air vent/manhole was included on the steel pipe directly downstream of the tunnel transition to provide additional redundancy against negative pressure formation and to provide additional dissipation of the air blast.

4.3 Existing Diversion Tunnel

One-dimensional hydraulic computations were completed to investigate the range of discharge capacities and flow conditions of the diversion tunnel. The diversion tunnel opening was specified to occur below a reservoir head of 34 m to limit the discharge. The reservoir level was selected to satisfy the submergence requirements for inlet-controlled discharge. This would allow the transition from inlet control to open channel flow to occur within the diversion tunnel. The requirements for the flow conditions within the diversion tunnel were designed to ensure sufficient shear stress to flush sediments, remove concrete rubble and blasted material from the inlet and plug removal and not allow debris accumulation.

The open-channel discharge was estimated to be approximately 110 m^3/s, and capable of passing floods up to the 5% probable monthly flood (risk of exceedance) with no upstream impoundment during the temporary diversion period of June to the end of September. At higher floods, the reservoir would start to refill. Flood routing studies were based on analysis of historical stream flow records and were completed for floods up to the 1% of the probable monthly flood to better understand the hydrologic risks and effects on the construction schedule (Bennet et al. 2025).

5.0 DAM STABILITY AND SAFETY

As part of the Dam Safety Performance Monitoring Program (DSPMP) of the facility, 15 potential failure modes (PFM) were identified and categorized related to the existing condition of the dam in accordance with FERC Part 12D Periodic Inspections. The existing PFMs were modified to include new PFMs related to modification of the operation of the dam and construction of the low-level outlet. The stability of the concrete structure was analysed with Finite Element Method (FEM). The geometry of the 3D structure was modelled using SolidWorks Simulation software for linear elastic analyses. Two 3D models were developed, one for the existing dam condition and the other for the modified dam with the new low-level outlet. The existing dam 3D model was used to for comparison purposes and to ensure applied loads and resistance were consistent with previous stability analyses. The FEM analysis of the dam and new low-level outlet was used for stress analysis and for interpretation of the computed structural behavior.

5.2 Stability Results

The stability analyses of the Copco No.1 dam with the new low-level outlet were evaluated to the FERC Gravity Dams stability and strength criteria (FERC 2016). The analyses indicated the stability and structural strength criteria for the loading conditions associated with the dam modification were satisfied. The concrete dam, when analysed for load and resistance for the extreme conditions (flood and seismic loads) remained stable and stresses on the structure are below the allowable limit.

The compressive and tensile forces are observed to be transferred to the foundation, confirming that the structure functions well as a gravity-arch dam. The 3D behaviour and force transfer were noted to increase the dam resistance to static and dynamic loadings better than the case of a conventional gravity dam.

The FEM analysis indicated low effective stresses within the concrete at the new outlet tunnel. The stresses did not exceed the allowable concrete tensile strength. Overall observation from the stability and structural analysis results indicated that the tunnel has minimal impact on the global stability of the structure.

6.0 CONCLUSIONS

This paper presents a summary of the hydraulic and dam stability studies that were completed to design the outlet works required to drawdown the Copco No.1 reservoir and divert the Klamath River during dam removal work. Key conclusions from this work are:

- Access to historical construction documents allowed the design team to better understand processes used for construction of the structures, their operation and interim design stages of the original structure. This information was used to inform the layout alternatives.
- Discharge capacity of the release facilities is critical to planning the required period to lower the reservoir. The reservoir drawdown must consider inflow flood routing during the drawdown period. The reservoir drawdown outlets were designed to evacuate the reservoir with floods up to the 1% probable condition.
- A good understanding of flow conditions for the outlet works is critical, high-velocity flow and negative pressures on the outlet works surfaces can lead to damage and erosion of surfaces. The adjacent structures exposed to high-velocity flows have the potential to be damaged from bank erosion or undermined.
- Modifications of a dam must ensure that all dam safety risks are identified, evaluated and measures are in place to mitigate the risks. The structure shall remain stable and satisfy strength and durability requirements during the work and operation of the modified dam.

The outlet works and diversion tunnel described in this paper were constructed, rehabilitated and operated by Kiewit between July 2023 and October 2024. Management of the upper Kalamth River Basin resulted in lower-than-average discharges on the Klamath River (Benett et al. 2025). This allowed early completion of the reservoir drawdown. The outlet works and temporary diversion performed satisfactorily. A photo of the Klamath River channel flowing through the former Copco No. 1 Dam site is shown in Figure 4.

Figure 4: Klamath River channel at the former Copco No. 1 Dam site, looking upstream. (Credit: Kiewit)

7.0 ACKNOWLEDGEMENT

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