Friction Reduction of Unlined Power Tunnels for Increased Power and Energy Production

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Abstract

Many hydro power plants throughout the world are fed by long pressure tunnels often constructed by the drill and blast method. Many of these unlined tunnels were designed and constructed considering the economics of the time and the expected loading of the power plant downstream of the power tunnel. Depending on their design, these longer tunnels will experience high relative frictional losses if operated at or above their original design capacity. If the generating units are increased in capacity, hydraulic losses are increased significantly. Some conventional methods to decrease the friction in existing unlined tunnels have been to either concrete line the tunnel, pave the invert, or use other expensive methods or materials. In this paper I would like to share my first hand experience with a power tunnel project where we decreased the frictional losses of the tunnel using a hammer mounted on a small excavator to selectively remove rock projections in the tunnel flow stream. On this project the work proved to have only a couple years pay back due to the improvements in flow and the limitation of maximum capacity due to the reduced head during times of peak plant loading. I believe that this method of selective friction reduction can be cost effective on some existing tunnel that have had large flow upgrades or because of the local markets for power make it highly beneficial to increase capacity and minimize frictional losses.

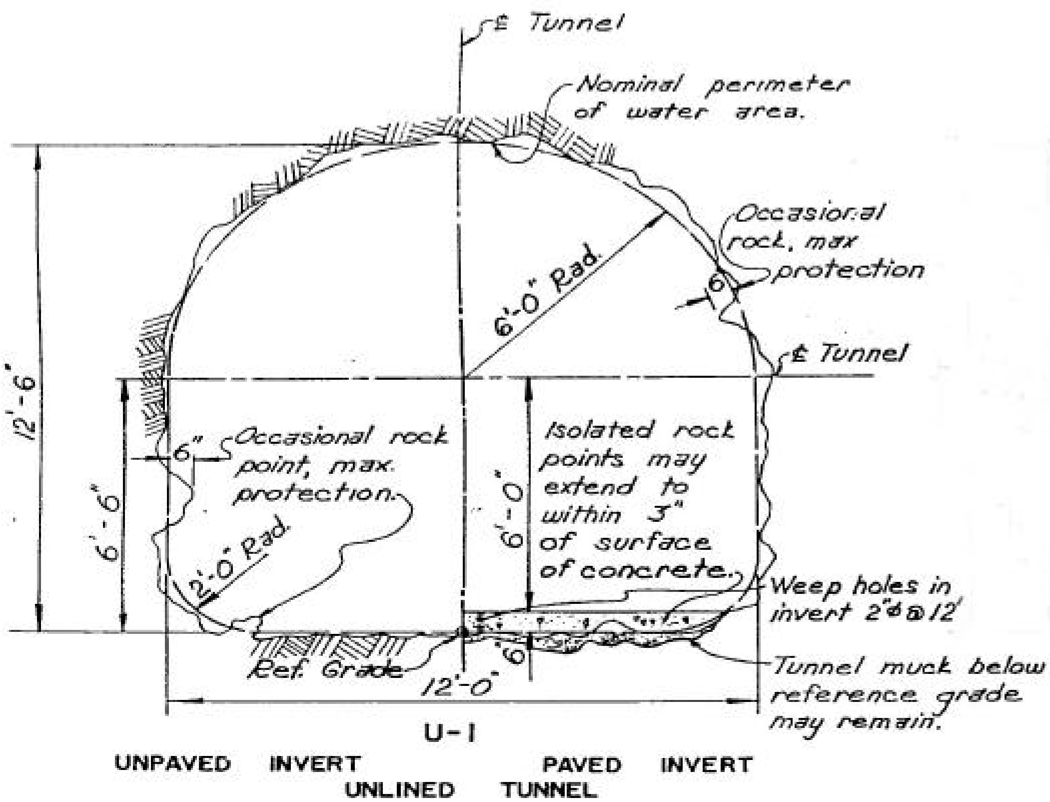
Introduction

Hetch Hetchy Water and Power is the municipal power and water supplier for the City and County of San Francisco. The bulk of the system's power comes from two separate water and power systems. The two adjacent water systems are in the Sierra Nevada Mountains and their primary source of runoff is snowmelt. One of the power plants in the Hetch Hetchy's system is supplied from Cherry and Eleanor Reservoirs. Water is released from Cherry Reservoir into a long tunnel and penstock. This water supplies Holm Powerhouse and it is returned to Cherry Creek. Due to operational changes as a result of the drought of the late 1980s, Holm Powerhouse is operated fewer months of the year and at higher loads. The recent escalation of power prices in the California market has shifted the operation of most hydro facilities in the region to provide more peak power when market prices are high.

Background

Cherry and Eleanor Reservoirs are connected together and jointly provide the water for the downstream Holm Powerhouse. The two reservoirs have an average annual runoff of approximately 327,000 Ac-ft. The power tunnel for Holm Powerhouse starts at the base of the dam at Cherry Reservoir and extends 29,426 ft to the start of the penstock. Approximately 90 % of the tunnel is unlined, horseshoe shaped, and constructed using conventional drill and blast methods. The power tunnel was driven through characteristic granodiorites of the Sierra batholith. An extremely steep penstock transports the water from the end of the power tunnel to the powerhouse. The penstock is 6805 ft in length and varies in size from 96" down to 80" at the bottom. This water feeds two six-jet pelton type turbine generators with an upgraded maximum combined capacity of 170 MW. The nominal design head on the turbines at full load is 2230 ft at a flow of 1000 CFS. These units produce approximately 650,000 MWH/yr.

As originally designed, the maximum total output of the plant was to be 135 MW with a flow of 810 CFS. The design load factor on the plant was approximately 55%. Economic studies done in the early 1950s had water conveyance and plant components sized for the relatively low capacity factor of the plant and maximum expected flow rates. Since the completion of the water conveyance system and power plant in 1959, many factors affecting the capacity and loading of the plant have changed. During the original study for the sizing of the power tunnel the value of addition energy was only \$3/MWH and addition power valued at \$17/kW-yr. The final design of the unlined tunnel sections resulted in a 12' diameter horseshoe shaped cross-section with a minimum cross section of 132.8 sq. ft.



Existing tunnel with unpaved invert

The design and construction was relatively straightforward for the time and geology of the region. Both ends of the tunnel are concrete lined due to the lack of ground cover for the expected pressures. Before the downstream lined section of the tunnel the design included a rock and sand trap. The rock and sand trap is 520 ft long with the tunnel enlarged to a 20 ft diameter horseshoe shape in the trap section. At the current higher flow rate of 1000 CFS it is estimated that the unlined sections of the tunnel produce 5.4 ft of head loss per 1000 ft of length.

Enlarged Rock and Sand Trap Tunnel Section (cleaned)

In the fall of 2000 the Cherry Power tunnel was dewatered to remove and clean the full rock and sand trap in the tunnel. The work was preformed by low bid contract. The method of rock and sand removal of the estimated 3000 yds of material was not specified in the contract. The method selected by the contractor was to use special two-yard diesel powered muck loaders and ferry the material out. The loaders used were Wagner Model ST-2D Diesel Scooptrams. The rock trap section of the tunnel was wide enough for this style vehicle to pass but not to turn around. As many as four tunnel muckers would work at one time traveling the 5000 ft of lined tunnel to dump their spoils as a group.

Cleaning end of Rock Trap. Note discoloration line showing filled area of trap.

To increase their production, governors on the primary drive engines were adjusted to allow higher vehicle speed on the trip into and out of the tunnel. Due to the small diameter of the lined downstream section of the tunnel from the rock trap no steering of the vehicles was required in this section. At the peak of production a three-loader crew could remove over 12 yards of material per hour. The tunnel outage was planned for a minimum of 45 days. This relatively high rate of material removal presented an opportunity for additional work to be done in the tunnel to reduce frictional losses.

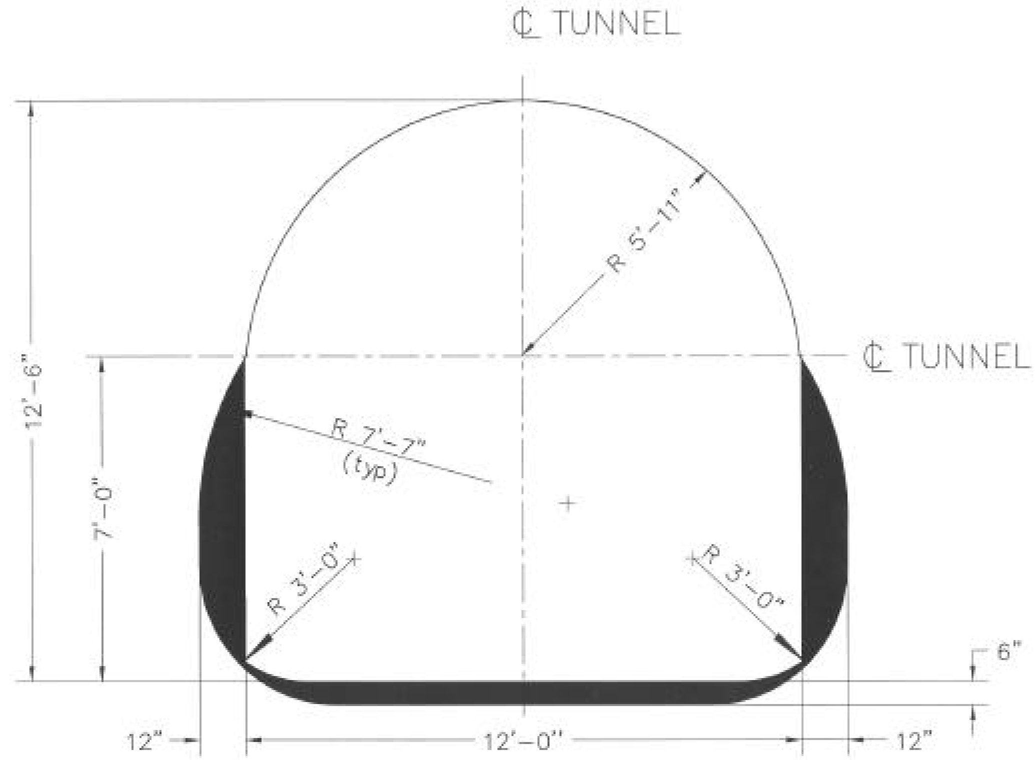
As allowed in the contract the contractor was directed to perform some trial work in the tunnel upstream of the rock trap. A "hydro ram" (ram hoe) attachment was added to the arm of a compact excavator. The excavator used was a relatively small unit that would fit through the smaller lined sections of tunnel. The unit was an IHI-30 JX Compact Excavator with a 33.3 Hp Izuzu engine. The machine operators were directed to break any rock protrusions that visually extended from the tunnel walls into the tunnel flow stream.

Tunnel excavator with bucket

The allowable area of tunnel wall work was from the mid height of the tunnel downward. The goal of the this work was to get data on production rates of rock removal and estimates on improved friction factors from smoothing the tunnel wetted surfaces and increased tunnel flow cross sections. This trial work proceeded well and operators used their own judgment on the amount of tunnel protrusion removal verse production effort. From this operating experience it was determined that the sharper the rock protrusion away from the base tunnel wall and floor the easier it became to break off the material.

Hoe Ram Attachment on Excavator Cleaving Rock Protrusion

It also follows that these sharp rock protrusions have the greatest negative affect on the overall tunnel friction factor. It is also is important to note that true surface contours of the tunnel walls have a much greater effect on the frictional losses then a small resultant increase in tunnel cross-sectional area due to material removal. The contract was modified and the contractor was directed to continue recontouring the tunnel walls and invert as time allowed. The contractor was offered a contract bonus of $145/yd of material broken from the upstream tunnel sections and removed. This was justified by the expected decrease in tunnel losses during periods of high power drafts. It was calculated that if the existing tunnel could be increased in size from 132.8 to 143.4 sq. ft and have make a large reduction in the "manning" friction factor". It was expected that we would see a 1.5 to 2.0 ft/ 1000 ft (tunnel) of head loss reduction at the 1000 CFS plant flow. This calculates to an approximate 1.5 ft of head loss reduction per 392 yds of material removed. Assuming a removal cost of $145/yd for the material, this equates to approximately $38,000 per ft of head reduction.



12" SIDE EXCAVATIONS AND 6" BOTTOM EXCAVATION
= 149.5□FT.
68.9 YDS/100'
PROPOSED CHERRY TUNNEL MODIFICATIONS

It was estimated that an additional 290 MWH/yr would be produced at the downstream power plant for every foot of head reduction at full load. Since the generating units are now turbine limited in output at less than full reservoir levels, the maximum generator output would also be increased 114 kW per ft of friction reduction. In terms of cost per generator capacity this equates to $332,000/MW for the increased capacity. The additional work proceeded well but production started to falter as the haul distances continued to increase as they proceeded farther up the tunnel. Contractor and owner agreed to stop work after this tunnel work had proceeded 3,300 ft up the tunnel from the rock trap. Work was halted due to the lack of remaining outage time and decreased production as a result of increased haul distances for the generated material.

The power plant was tested for maximum output before and after the cleaning of the rock trap and additional tunnel work performed. With a three-foot lower forebay (reservoir) level, and no modifications made to the turbines or generators, the maximum combined plant output increased 1.82 MW. It is estimated that the rock trap cleaning resulted in a 3 ft reduction in losses and extra tunnel work an additional 14 ft head loss reduction at full load. This increased output appears high for the work performed. It could be speculated that the friction losses due to the almost full rock trap were much higher then expected.

Conclusions

A goal of most existing hydro owners is to increase the production and output of the facilities. On many older high head plants the plants water conveyance systems were sized on the economics and original loading and capacity of the facilities. The increase in energy value and volatile price of peak power has caused many facilities to look at increasing the maximum capacity and peaking ability of their facilities. Many high value plants have performed the conventional improvements on their generating equipment. Often the head losses component in the water conveyance system is overlooked for possible improvement due to difficult nature of making economic friction reduction in the total facility. Several conventional methods of friction reduction used in unlined tunnels are very costly to make. Tunnel improvements such as tunnel lining, invert paving, or enlargement can be often large and costly projects with long paybacks periods. The tunnel smoothing work done in the Cherry Power tunnel had a very low unit cost and has proved to make measurable reductions in head losses and increased plant output. This proposed method should work better if material transport issues can be improved. In the case of Cherry Power Tunnel the upper end of the tunnel could be reworked for a lower unit cost due to the much shorter haul distances for the generated rock produced during the tunnel smoothing work. Due to the easier access to the upper end of the tunnel it is anticipated that 10,000 to 15,000 ft of tunnel lining could be enlarged and smoothed and have a project payback of less than 5 years. The easiest tunnel sections to enlarge are those closest to the access portals. Any proposed tunnel enlargements and improvements often have diminishing returns in proportion to the amount of enlargement and haul distance for the tunnel spoils.

References

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