FEATURE ARTICLE

Evolution of a mega project: Update on the Bay Delta Tunnels

Water drawn from the Sacramento-San Joaquin Delta provides water supply to 66 percent of California's population and supports the state's agriculture industry. The existing through-Delta water system is outdated and unreliable with environmental risk to some fish and wildlife species. The Bay-Delta Conservation Plan (BDCP) has been established to environmentally retrofit and modernize California's water delivery system through the Delta by restoring habitats, constructing new diversion points in the north Delta and providing a means to transport water supplies under the Delta, rather than through sensitive natural channels.

Under BDCP, the Delta Habitat Conservation and Conveyance Program (DHCCP) has developed several alternatives to convey water from the Sacramento River in the north to the existing pumping facilities in the south Delta through an isolated conveyance system. The new conveyance system would become an integral part of the State Water Project (SWP) and the federal Central Valley Project (CVP) by transporting water to the export pumping plants for each of these projects. The DHCCP is managed by the California Department of Water Resources (DWR), while state and federal water contractors provide technical support to the program.

The initial conceptual study efforts on the overall program commenced in 2007 and examined various options for the proposed conveyance system. Several conveyance alternatives were analyzed at that time. The Conceptual Engineering Report published on Oct. 1, 2013 identified the modified pipeline/tunnel option (MPTO) as the preferred alternative to be included in the BDCP environmental documents. MPTO includes three river intakes and pump stations along the Sacramento River, various sizes of pipelines and tunnels, junction structures and two forebays that are capable of delivering up to 4 million gpm (9,000 cfs) from the Sacramento River to the SWP and CVP. The river intakes are located near Hood in Sacramento County approximately 64 km (40 miles) from Clifton Court Forebay (CCF) in Contra Costa County. This route would cross portions of Sacramento, San Joaquin and Contra Costa counties. Figure 1 depicts the configuration of the MPTO alternative.

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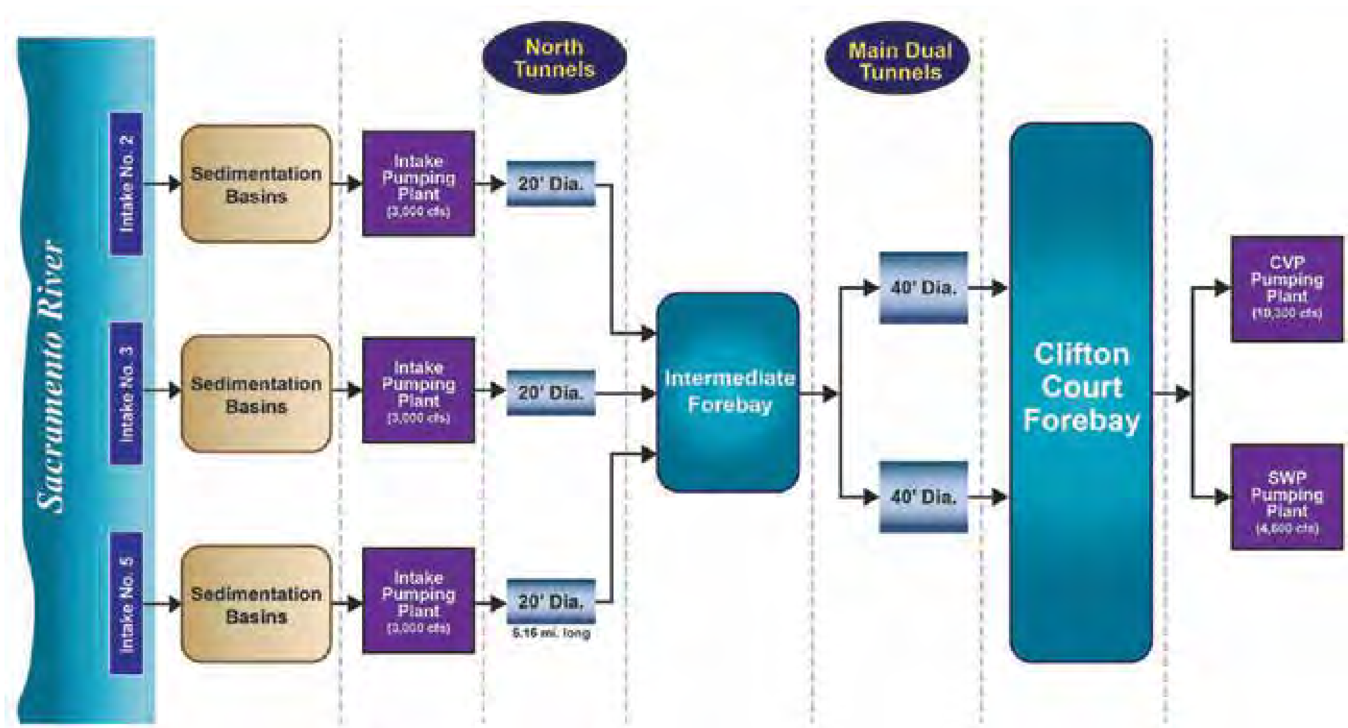
DWR, managing the design and construction of the conveyance facilities, initiated further optimization of the MPTO configuration. The primary goals of the optimization effort included (1) reducing environmental impacts of the proposed facilities along the Sacramento River and (2) identifying a project configuration that would place the concrete segmental tunnel liner systems into compression during system operations instead of the MPTO case, which caused the liner system to be in tension during operations. Clifton Court Option (CCO) was structured to address both of these issues. The CCO alternative retains the project's major design criterion of: maximum velocity of 0.06 m/s (0.2 ft/sec) at each intake fish screen two maximum total flow take of 4 million gpm (9,000 cfs) from the Sacramento River (1.3 million gpm or 3,000 cfs per each intake). Figure 2 depicts the CCO configuration with the main project pumps facilities located at Clifton Court Forebay, the extreme south terminus of the project. Figure 3 depicts the anticipated differences in the hydraulic profiles between the MPTO and the CCO in a simplified side-by-side comparison. Project designers found that the MPTO hydraulic configuration led to the tunnel lining systems being subjected to internal tension due to high hydraulic grade lines. Conversely, the CCO configuration places the tunnel lining systems in compression due to the lower anticipated hydraulic grade lines.

The significant components for the MPTO that are revised under CCO modifications include the following:

- Combining and relocating the three individual pump stations from the Sacramento River to the terminus of the project at Clifton Court Forebay.
- Modifying the intermediate forebay (IF) to work in conjunction with the new pump configuration.
- Revising piping, gates and controls at each of the three river intakes.
- Revising tunnel diameters for the three north tunnels.
- Modifying tunnel segmental lining systems to

FIG. 1

MPTO configuration with intake pump plant on the Sacramento River.



take advantage of reduced hydraulic grade conditions.

The engineering technical efforts that were conducted to support the development of the CCO represent a refined "proof of concept" analysis, and are considered to be conceptual in nature. This work effort was not intended to be an in-depth review of all the technical aspects of the CCO. The more detailed analysis of the remaining technical aspects of the concept will be further developed in preliminary design.

CCO tunnels

North tunnels. The CCO alternative relies on gravity flow from the Sacramento River to the IF, and then down to the CCF pumps stations. As such, hydraulic losses into the north tunnels must be reduced from those that are experienced in the MPTO alternative in order to successfully implement the CCO alternative. Consequently, north tunnel sizes under the CCO were increased from the MPTO as shown in Fig. 4. The diameters are approximate and should be further refined in preliminary design.

Main tunnels. Under the CCO alternative the size of the twin main tunnels remains unchanged from the 12-m (40-ft) inside diameter that is utilized in the MPTO.

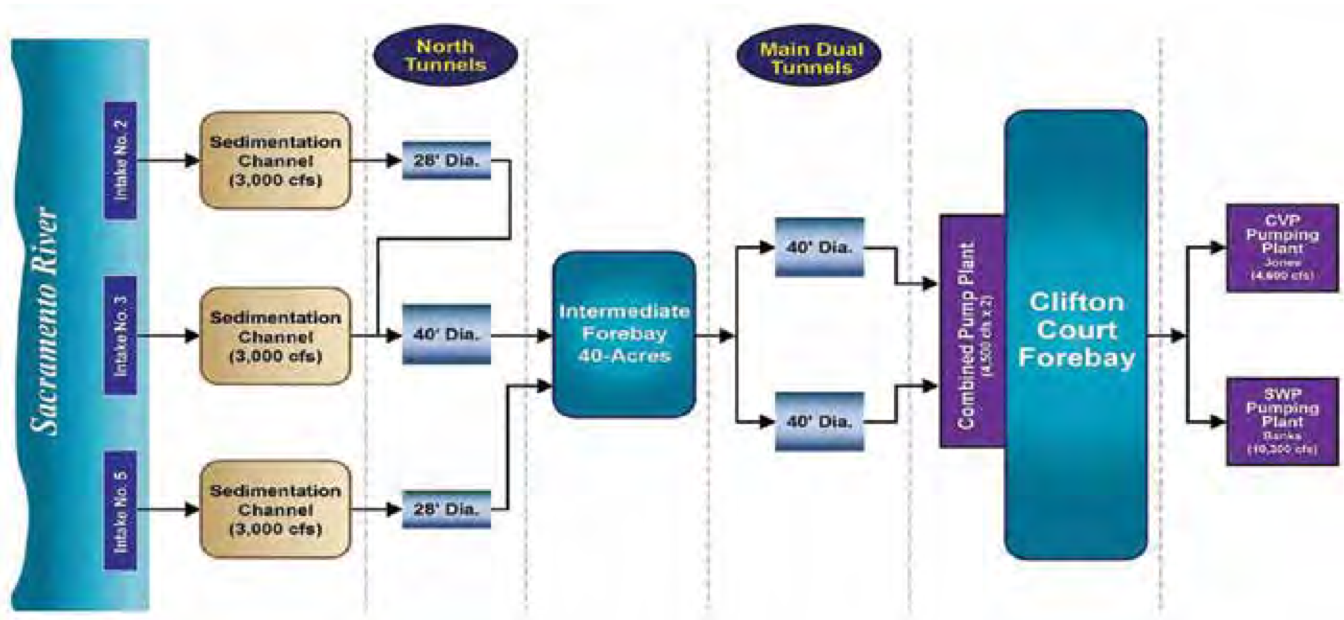
Tunnel segmental liner criteria. For the purposes of designing the segmental liner for the tunnels, the overall tunnel system can be divided into two regions, namely the north tunnels section and the main tunnels section. North tunnels deliver water from the three river intakes to the IF, and the main tunnels convey water from IF to the Clifton Court Forebay (CCF). The inside diameters of the north tunnels vary for each proposed option (MPTO or CCO), while the inside diameter of the main tunnels remains constant at 12 m (40 ft) under both alternatives.

Early in the planning process for the overall tunnel system, it was determined that a single-pass tunnel liner system could be utilized as a cost effective lining system. The tunnel liner system consists of precast concrete segmental liner with bolted-gasketed joints, and there is no steel second-pass liner in the tunnels. For the main tunnels, it is anticipated that a nine-piece ring configuration would be used with segment thickness of approximately 508 mm (20 in.). The segments (up to 7,000 psi strength) will be cast and steam-cured in concrete segment plants under strict quality control measures. Reinforcement will consist of traditional steel reinforcement and steel fiber as required to increase durability and provide crack control.

Under the single-pass liner design, a typical joint between segments will include a gasket to seal against water seepage and alignment bolts for tunnels subject to compression load only. If the segment ring is subjected to internal tension load, as was anticipated under the

FIG. 2

CCO configuration with intake pump plant at Clifton Court.



MPTO arrangement, special positive connection across the joint and tension reinforcement are necessary to transfer the tensile force throughout the segments. Historically, it is uncommon that a bolted-gasketed tunnel liner system is subject to net tension in soft ground conditions. However, under the MPTO, this is the case. Therefore, substantial research and analysis were conducted during the study phase to ensure feasibility and constructability.

In addition to strength requirements, leakage control through the liner is essential to ensure liner performance. Excessive leakage through the liner would lead to potential soil erosion, hydraulic fracturing and loss of liner support. In the long run, deterioration of the tunnel liner could occur. In addition, water leakage from the tunnel to the surrounding soil translates to economic loss.

The performance criteria for the tunnel liner system dictated that the liner be designed for all the following load cases to ensure reliable performance during the minimum 100-year design life of the system:

- Full external ground load and external ground water pressure.
- Net internal pressure (difference between internal hydraulic pressure and external ground water pressure).
- Ground strain associated with seismic design.
- Segment handling loads such as lifting, hosting and TBM pushing.
- Crack and leakage control performance criteria.

For the net internal pressure design of the liner, the external ground water pressure can be assumed to be at elevation 0.0 (MSL) along the majority of the alignment. Occasionally, lower ground water elevation may occur, and the lowest probable elevation is less than 3 m (10 ft) at isolated locations. Currently, the tunnels are planned to be constructed with an invert depth of approximately -42 to -45 m (-140 to -150 ft). Further geotechnical exploration will identify and confirm the ground water elevation along the alignment. Additionally, ground overburden to counteract the internal hydraulic pressure was ignored at this time as a measure of additional conservatism due to the concept-level work underway and the lack of geotechnical data to justify the overburden.

Using the same tunnel design criteria stated above for each option (MPTO or CCO), the following areas were evaluated:

- Loads on tunnel using results of preliminary hydraulic analysis.
- Modifications to tunnel design for each option.
- Advantages and disadvantages of MPTO and CCO.

Tunnel liner design of the MPTO

Under the MPTO option, each river intake facility consists of a pumping plant that pumps water from the river and conveys it throughout the system. Based on the pumping scenarios at the intake, a summary of the hydraulic grade line (HGL) is shown in Fig. 5. The MPTO HGL is called out on the figure, and the CCO HGLs are shown below the MPTO HGLs. Given

FIG. 3

Simplified hydraulic configuration comparison MPTO vs. CCO.

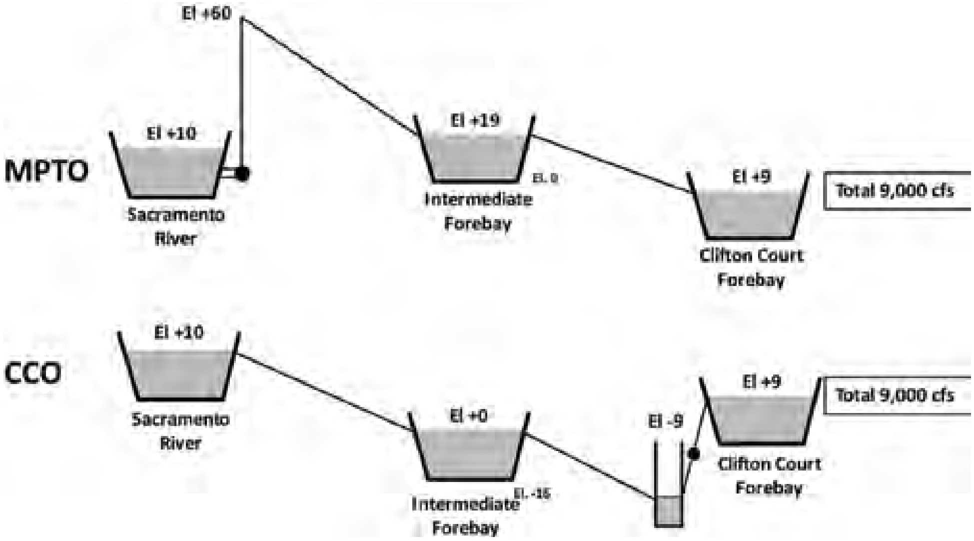
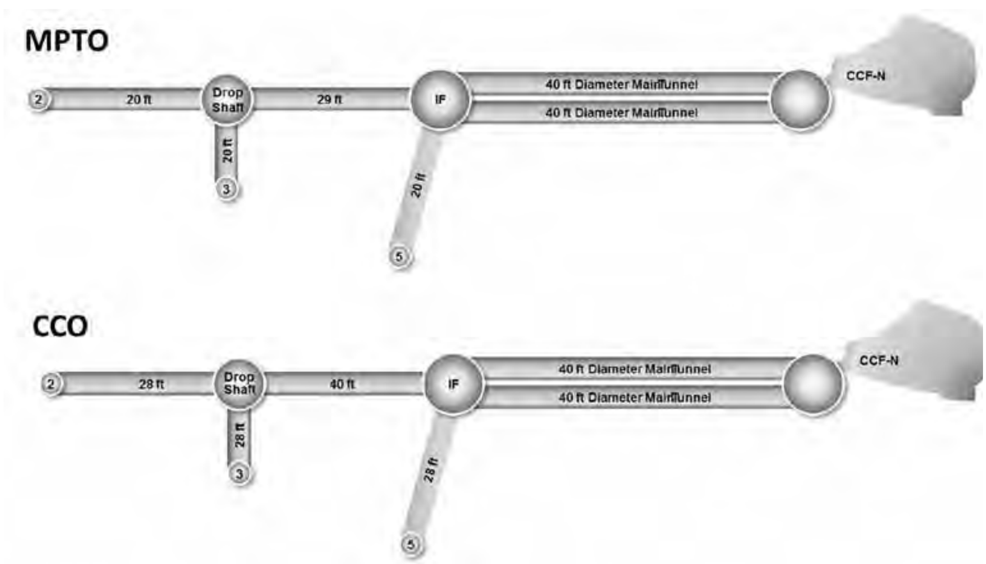


FIG. 4

Tunnel diameters: MPTO vs. CCO.



that the HGL for the MPTO is always higher than the external ground water elevation. Both the north tunnels and the main tunnels are always in tension during normal operation. Figure 5 shows the HGL for both the MPTO and CCO along the tunnel alignment from the river intake to CCF. Since the flows and hydraulic grades of CCO are dependent on the river elevations, both the normal high +3 m (+10 ft) and normal low +0.3 m (+1 ft) elevations are shown with the respective hydraulic grades. The mean ground water elevation is assumed to be at 0.0 (MSL).

One solution to this structural design challenge in order to provide tension capacity for the liner is to use a bolted connection similar to the San Diego South Bay Outfall project. Figure 6 shows the schematic design, and Fig. 7 shows an in-fabrication photo of the segment for the South Bay project. The South Bay project had similar hydraulic design parameters as the MPTO tunnels. However, the South Bay tunnels were only 3.3-m (11-ft) ID.

Given the high tensile loads associated with MPTO, the tensile reinforcement consists of high-strength hoop bars up to #11 and bolts up to 42 mm (1.625 in.) in diameter. The use of hoop reinforcement provides a positive connection across the segments with sufficient ductility to handle the high-tension force. However, the special connection increases ring-build time, complicates segment alignment, increases segment manufacturing cost, increases tunneling cost and leads to longer construction schedule. Additionally, it is anticipated that a PVC T-lock liner may have to be installed in the tunnel to further reduce the risk of leakage from the tunnels.

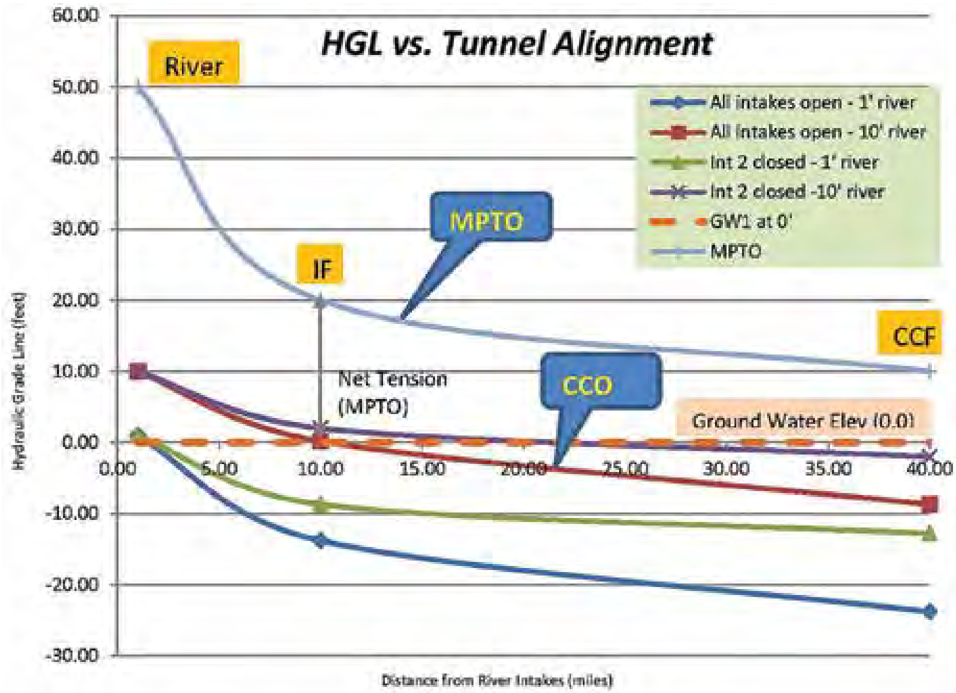
Tunnel liner design of the CCO

Under the CCO, a combined pumping plant is located at CCF with control gates at each river intake. Using results from preliminary hydraulics study, the HGL elevations of the CCO alternative that were previously shown in Fig. 5 are now summarized in Table 1 at a flow rate of 4 million gpm (9,000 cfs). As this table and the figure show, under the CCO alternative, the HGL inside the tunnels is greatly reduced from the MPTO alternative. Under the MPTO option, with the smaller north tunnels, the river intake pumps had to lift the water to elevations more than 15 m (50 ft) in order to ensure that the water would flow by gravity to Clifton Court forebay. Under the CCO option, with the larger northern tunnels, it is possible to flow 4 million gpm (9,000 cfs) all the way to the CCO pump plant under a variety of river elevations as shown in Table 1.

In fact, under the CCO alternative, Table1 shows that the main twin 12-m (40-ft) tunnels will most likely have HGLs that are equal to or less than the ground water elevation. For tunnel locations with HGL at or below the ground water table, the tunnel liner will be in compression only, which is the design condition for the majority of concrete segmental liner constructed today. No special tension bolts or hoop reinforcement will be required for a compression-only liner. It is anticipated that the compression-only segment design will yield significant cost savings and schedule improvements compared to a tension-compression system.

FIG. 5

HGL vs. tunnel alignment under various operational conditions.



For regions where the HGL is higher than the ground water elevation for the north tunnels, net tension will develop in the liner, but the corresponding hoop tension force is 55 percent to 80 percent less than the original MPTO design under normal pumping operation. For extreme flood river elevations of 6 to 7.5 m (20 to 25 ft) under CCO, design considerations on ground overburden, backfill grout, ground permeability, concrete tensile strength will be considered during preliminary and final design to ensure the liner will provide strength and leakage control.

Comparison of the MPTO and CCO tunnels

Under the CCO pumping scenario, the net internal hoop tension on the segmental liner can be substantially reduced or eliminated. This will significantly reduce overall tunnel costs, and reduce leakage risks.

Advantages of CCO for tunnel design can be summarized as follows:

- 12-m (40-ft) main tunnels 48 km x 2 = 96 km (30 miles × 2 = 60 miles) are subject to compression-only loading for the majority of the tunnel alignment between IF and CCF. The elimination of tension on the liner implies that special high-strength tension bolts are not required at the joint and additional hoop reinforcement is not necessary in the segment. Additionally, the T-lock liner inside the tunnels will not be required. Under this situation, liner construction utilizes conventional proven tunneling methods for better production and lower costs than presently planned under the MPTO.
- Leakage from the tunnel to the surrounding soil is eliminated if the tunnel is always under compression. The absence of net tension minimizes crack formation and propagation in the concrete segments, which will provide a durable and reliable conveyance liner system. This reduces the probability of soil erosion behind the liner, ground support loss and minimizes economic loss.
- For the north tunnels (between river and IF), net

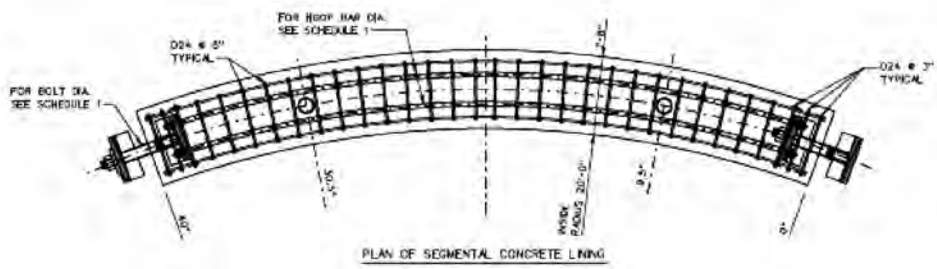
TABLE 1

HGL elevations for each option.

Option	Intakes	River Elev (ft)	IF Elev (ft)	CC Elev (ft)
MPTO	—	+50*	+20	+10
CCO	All intakes open (9,000 cfs)	+10	+0.2	-8.7
		+1	-13.8	-23.8
*Pumping at river intakes.				

FIG. 6

Preliminary reinforcement for Bay Delta Tunnels (MPTO).



tension will likely remain given the variable river elevations. However, the tensile force magnitude is substantially reduced for CCO because the HGL was reduced. Maximum probable high water HGL is 3 m (10 ft), which is only 20 percent of the net internal pressure of MPTO 15 m (50 ft). Hoop stress is also reduced as some of the north tunnel diameters are smaller than the main tunnels. Because the tension force is reduced, joint bolting and hoop reinforcement will be reduced. In addition, other tension-resisting devices (e.g., shear cones) may become viable because the tensile load is decreased. The T-lock liner will most probably not be needed on the north tunnels for leakage control.

- Eliminating net tension along the majority (or all) of the main tunnels and decreasing tension in the north tunnels will benefit DHCCP. The CCO alternative optimizes liner design, reduces construction costs, increases tunneling production rates, shortens construction schedule and eliminates some of the long-term potential risks associated with tension design of the large-diameter, high-pressure segmental liner.

FIG. 7

San Diego Bay outfall segment reinforcement.

Combined pumping plant at Clifton Court

General site layout and configuration. In the CCO approach, the northeast corner of Clifton Court Forebay serves both as the terminus of the 12-m (40-ft) tunnels, and location of the new combined pumping plant. At this location, there is a small island within DWR's property holdings that is suitable for constructing the needed facilities.

The facilities arrangement at this location consists of the main tunnels, surge shafts and twin deep-shaft pump plants. The proposed facilities are shown in Figs. 8 and 9. The surge shafts provide a point of interconnection between the 12-m (40-ft) tunnels and this provides for increased operational reliability and flexibility. Further south of the surge shafts are the deep-shaft pump plants that house the pumping equipment. The diameters of the pump shafts are larger than the surge shafts so the pumps and other equipment could be adequately arranged. The distance between the surge shafts and the pumping shafts was set at a minimum of 137 m (450 ft) to provide working separation for the tunneling contractors and the pump station contractors.

Surge shafts. Each 12-m (40-ft) tunnel connects to a 46-m (150-ft) diameter surge shaft. The surge shaft is divided into three sections for reliability and operational flexibility. The surge shaft has the following operational functions:

- **Surge protection:** In the event of a hydraulic surge in the tunnel system, this shaft is configured with an unrestricted opening above each weir gate that will allow water to spill over into Clifton Court during a surge event. Surge discharge channel is shown in Fig. 8.
- **System isolation:** A platform wall at the center of the shaft is used to divert water flow vertically up the shaft where six isolation drop gates are located. During tunnel maintenance and dewatering activities, these gates can be closed to isolate one of the twin tunnels from the rest of the system.
- **Flow diversion:** The two surge shafts are located side-by-side. Four drop gates between the two shafts are used to divert

water flow from one shaft to the other allowing the use of both pumping shafts interchangeably. This operation flexibility allows the use of either pump shaft during maintenance and repairs.

- **Gravity flow operations:** Under certain river stage conditions and water levels in CCF, it may be possible to convey water from the river to CCF entirely by gravity. Under such conditions, water will rise in the surge shaft and spill into CCF in the same manner that water would spill from the shaft in a surge event. Water will not flow through the pump shaft in the gravity operation mode.

FIG. 8

Cross section of CCO surge shaft and pump shaft.

Pump shafts. Downstream of the surge shaft, water flows into the pumping plant shaft via short 12-m (40-ft) tunnels. Two pump shafts have a capacity of 2 million gpm (4,500 cfs) each, for a total of 4 million gpm (9,000 cfs). The pump suction receives water flow from the center of the shaft. The configuration allows for an even hydraulic flow split among all the six pumps (five duty and one spare). Each pump is sized for 4 million gpm (9,000 cfs) for a max flow capacity of 2 million gpm (4,500 cfs) per pump station shaft. Two low-capacity pumps, 135,000 gpm (300 cfs) each, will be used during low flow conditions to avoid running the rpm on the large pumps down to a speed that may cause thrust bearing issues, and for draining the pump wet well during pump inspection and repairs.

The water level in the Sacramento River elevation varies from elevation 0.15 m to elevation 7.3 m (0.5 ft to 24 ft) above sea level, and the Clifton Court Forebay elevation varies from elevation -0.6 to 1.8 m (–2 ft to 6 ft). Hence the pump stations must be able to operate over a wide operational range. In order to select appropriate pumps the discharge side at Clifton Court Forebay will be fixed to elevation 3 m (9 ft). Three system curves and operating conditions were determined using the fluctuation in elevation of the river and the fixed discharge elevation at the Clifton Court Forebay. The three system curves consist of (1) a high head curve, (2) a low head curve, and (3) a design condition curve. The design condition curve was interpreted as being a typical river elevation of 1 m (3 ft), which will be the typical operating condition.

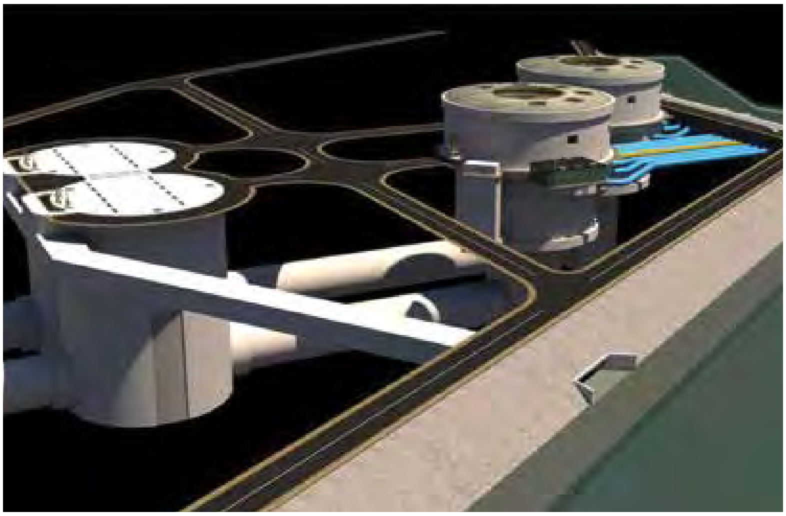
At the design operating condition of 4 million gpm (9,000 cfs), the total dynamic head of 10 m (30.3 ft) is required to pump into Clifton Court. The projected total dynamic head from the river to the pump shaft has a head loss of 5.8 m (19.3 ft) based on the hydraulic model that was completed for this study. The total horsepower for the CCO arrangement under design head conditions is approximately 25,000 kW (34,000 hp), compared to the MPTO system which has an installed horsepower requirement of 42,500 kW (57,000 hp). The difference between the two options is 17,200 kW (23,000 hp). It is believed that the CCO arrangement will provide an opportunity to run the system in a "full gravity mode" under some flow ranges conditions. The MPTO does not provide a gravity flow option pumping is required for all the flow ranges.

System hydraulics – real-time modeling

Due to the innovative nature of the CCO, it was determined that a real-time model was needed to evaluate system response and hydraulic performance based on demand patterns in the river and the proposed intake deliveries. The model was used to help identify any fatal flaws in the hydraulic and operation aspects of the CCO alternative. Some of the key points of interest included in this dynamic model analysis were the following items: (1) river intake flow control, (2) intermediate forebay fluctuations, (3) pump operation, (4) overall flow delivery capabilities and (5) upset/stress condition analysis. The real time model was not intended to provide surge/transient analysis. The system surge analysis will be conducted in the future (i.e., preliminary design). As previously discussed, the CCO system layout provides a large surge shaft/chamber immediately upstream of the pumps and any pump "trips" will discharge water from the surge chamber back into Clifton Court Forebay. Therefore, on a conceptual basis, it is believed that the overall system is adequately

FIG. 9

3D rendering of surge and pump shafts with tunnels (view to east).



protected from hydraulic surge events by these surge shafts.

Hydraulic model analysis. The hydraulic model was used to evaluate extreme operating conditions and determine the effects on the overall CCO conveyance system. The flow data used for the analysis consisted of data supplied by DWR from previous BDCP-related hydraulic studies. The main analysis included ramping up of the pumps to achieve a range of flow conditions and durations up to a maximum total system flow of 4 million gpm (9,000 cfs) from intakes 2, 3, and 5 consisting of 1.3 million gpm (3,000 cfs each) and then transitioning to an emergency shutdown of intake 2, to a new steady state system flow of 2.6 million gpm (6,000 cfs). These conditions were analyzed to determine the fluctuations in the Intermediate Forebay elevations and if the following two criteria were exceeded: (1) fish screen velocities not to exceed 0.2 fps at any time, and (2) flow per intake not to exceed 1.3 million gpm (3,000 cfs) at any time.

Some of the key conclusions that were obtained from the real-time hydraulic modeling include:

- The CCO alternative can deliver the desired flows to CCF under all operational scenarios set forth in the project criteria.
- Overall, under both normal operating conditions and extreme stressed conditions, the system performances are unaffected by relocating the pump stations from the intakes to Clifton Court Forebay.
- At steady-state flow from each intake, some gate throttling at the exit from the sedimentation basins at the river intake structures will be required to balance the flows equally. Alternatively, the flows can be balanced without throttling gates by further refining the size of the northern conveyance tunnels to each intake accordingly. This analysis will be conducted in preliminary design.

Conclusions

The CCO configuration for the DHCCP was developed to address several different challenges related to the design, construction and operation of the new conveyance facilities. The existing concept, referred to as the MPTO, presented significant technical challenges related to the design of the segmental tunnel liner due to the high pressures that were anticipated inside the tunnel during operations. Additionally, the MPTO configuration placed large industrial-type pumping and support facilities in close proximity to environmentally sensitive features along the Sacramento River. The CCO alternative combines and moves the pump stations from the river intake facilities and places them near the terminus of the project at the Clifton Court Forebay. Under this configuration, water will flow by gravity from the river to the pump station, from which point it is lifted into Clifton Court by two identically sized pump stations. By utilizing gravity flow through the north and main tunnels, operating pressures in the tunnels are reduced, thereby simplifying the design of the tunnel's segmental liner system. Relocation of the main pumping plants from the river intakes reduces the amount of construction required in an environmentally sensitive area, and eliminates the need for permanent high voltage transmission lines, and long-term operational activities in these areas. ■