Stream Simulation Design of Conn Creek Culvert

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Abstract

Conventional culvert designs based on hydraulic capacity often result in high velocities or inadequate water levels that are not conducive for fish migration. For fish-bearing stream crossings, alternative designs need to be developed in order to secure timely approval from Fisheries and Oceans Canada (DFO). Stream simulation is one of those alternatives. It was proposed to, and accepted by, DFO for the Conn Creek Culvert replacement in Fort McMurray, an environmentally sensitive site due to the controversy over Alberta oil sand projects.

The existing 4.2 m diameter, 82 m long culvert carries four lanes of Highway 63 traffic across Conn Creek, a tributary to the Athabasca River. As part of the $530 million Highway 63:11 upgrading project, the existing culvert required extension. During the review of the proposed alternatives, DFO cited the high flow velocity within the existing culvert as a barrier to fish passage, resulting in the separation of upstream and downstream habitats. Authorization for the works would need to ensure fish passage was restored.

Challenges encountered during the design and construction of the replacement culvert included:

- Traffic accommodation for a busy highway with over 50K Average Annual Daily Traffic (AADT)
- Tight construction schedule demanding a quick approval from DFO
- Providing fish passage for weak swimming fish species across a 120 m span
- Enabling fish passage by reducing flows and providing velocity refuge while also addressing constructability and economics.
- Reducing flow velocity in a system that had been significantly altered historically (stream length shortened by removal of large meander sections of the natural stream).
- Shallow limestone bedrock demanding blasting for closed bottom culvert installation
- Owner's concerns of high construction cost and potential scouring of open bottom culvert

This paper presents the background of the project, the existing fisheries, and details of the stream simulation design used to satisfy regulatory and project requirements. It is also the authors' intention to share their experiences and lessons learned in securing a timely approval from DFO on an extremely tight schedule.

Introduction

As oil sands output has grown, the population in the Fort McMurray area has doubled in the last ten years, with most of the additional population residing in new developments north of the Athabasca River [1]. Population increases are straining the city's infrastructure, especially on Highway 63, the sole highway that leads into Fort McMurray from the south and the only connection to the oil sand projects north of Fort McMurray. Currently Highway 63 serves as a commuter road, truck route, high-load corridor route and a dangerous goods route mixing heavy industrial traffic with smaller commuter traffic across a narrow highway with only two lanes in each direction to accommodate a traffic volume over 50K AADT [2]. The high commuter population within Fort McMurray creates unruly bumper-to-bumper traffic during peak hours. To relieve the congestion, the Alberta Government secured a budget of $530 million to upgrade Highway 63 to six core lanes with additional collector and distributor (CD) roads in each direction from Franklin Avenue in the south to Confederation Way in the north. The project includes Franklin Tunnel, a new 5-lane Athabasca River Bridge, Conn Creek Culvert replacement, superstructure replacement and widening of the existing Steinhauer and Grant MacEwan Bridges, tangent pile walls at the pinch point north of the bridges, and interchanges at Thickwood Boulevard and Confederation Way (**Figure 1**). In 2006 Alberta Transportation (AT) retained the consortium of AECOM, Stantec, and CH2MHill to provide design and construction management for the project. It was the largest conventional delivery project in AT history.

Conn Creek intersects Hwy 63 at Station 15+667.0, less than 500 m north of the proposed Thickwood Interchange (**Figure 2**). At this crossing, Hwy 63 will be expanded to six core lanes, a 2-lane northbound CD road, one lane southbound CD road, and on/off ramps for the Thickwood Interchange. The existing culvert needs to be extended at both ends from 82 m to approximately 138 m (**Figure 3**).

Existing Conditions

Existing Structure

The existing structure is a 3800 mm (span) x 4190 mm (rise) SPCSP culvert with invert to invert length of 82 m. It was constructed in 1981 during the twinning of Hwy 63. Currently it carries two-lane traffic in each direction over Conn Creek. Conn Creek was realigned during the culvert installation. The realignment of the channel effectively reduced the channel length by over 100 m, thereby increasing the slope of the channel adjacent to the road (**Figure 4**).

The latest condition inspection of the culvert was carried out in the spring of 2008. Longitudinal cracks were identified on some of the rings. The estimated remaining service life was 5 years. **Figure 5** shows the culvert during the spring runoff in 2006.

Geotechnical Investigation

Limestone was encountered in all three test holes at depths ranging from 4.6 m to 5.2 m below existing ground surface and 0.5 m below the streambed. For closed bottom culvert installation rock excavation/blasting is required. For an open bottom arch culvert or a bridge structure the limestone bedrock is suitable for a spread footing. However, AT best practice guidelines recommend the use of pile foundations for all river crossing structures.

Hydrotechnical Investigation

The basin originates approximately 25 km west of the site and is an average of 4 km wide throughout. Based on air photos of the study reach, the creek is characterized by meandering channels both upstream and downstream of the crossing at Hwy 63. The creek flows from west to east and discharges into the Athabasca River approximately 620 m downstream (**Figure 6**). The topography consists of mainly undeveloped native forests ending in developed lands in the City of Fort McMurray. The main channel consists of some shrubs and bushes on the side slopes and scattered stones on the streambed.

The longitudinal slope of the creek was estimated to be 0.0162 m/m over a distance of approximately 292m upstream of the crossing. Downstream of the crossing, the slope was estimated to be approximately 0.0045 m/m over a distance of approximately 311 m. In general, the stream is characterized by a steeper profile slope upstream of the crossing than downstream, where it approaches the Athabasca River.

Using the AT Channel Capacity Calculator, the channel capacity design discharge (Qcc) was estimated to be 25.2m^3/s, which is within the basin run-off potential discharge estimate. At this discharge, flow velocities between 3.4 and 3.8 m/s are generated through the culvert, the culvert is flowing partially full, and the inlet will not be submerged.

By comparing the computed velocities at different cross-sections in the creek and within the culvert, it is apparent that the existing culvert poses a barrier for fish migration along the stream. The existing culvert has very little burial depth and is installed at a steep slope of 0.011 m/m, making it difficult for fish to swim upstream.

Fisheries

Conn Creek historically supported populations of Arctic Grayling, with the last confirmed observation occurring in 1972. In addition, fisheries research data indicates that Fathead Minnow, White Sucker, Brook Stickleback, Northern Redbelly Dace, and Pearl Dace had been found in the watercourse.

Fish presence surveys conducted in 2006 captured Lake Chub, Finescale Dace, Emerald Shiner, Brassy Minnow, and White Suckers, only within the reaches downstream of the existing culvert. Surveys in 2003 obtained Northern Pike, Pearl Dace, Northern Redbelly Dace, and Longnose Sucker downstream of the culvert. One survey in 1994 at the confluence of Conn Creek and the Athabasca River obtained Northern Pike, Walleye, Goldeye, Burbot, Longnose Sucker, White Sucker, Flathead Chub, Lake Chub, Longnose Dace, Emerald Shiner, Fathead Minnow, Trout-Perch, and Brook Stickleback. The only species of special concern is the Northern Redbelly Dace, which is listed as “Sensitive” in the province of Alberta.

Fisheries habitat in the area of the proposed bridge crossing was determined to be excellent overall. The cobble/boulder substrate lining the channel was moderately clean, and water quality was considered very suitable to support fish. Although aquatic vegetation was sparse due to pronounced currents and a lack of suitable silt or sand based substrates, riparian vegetation (mostly shrubs, grasses, and forbs) was well established and provided good overhanging cover for fish and protection against erosion. Spawning habitat suitability within the potential zone of impact was considered excellent due to abundant cobble and gravel substrates, which provide suitable spawning for Longnose and White Suckers, Walleye, Goldeye, Burbot, and many species of forage fish. The main channel of Conn Creek surrounding the highway crossing location provides excellent instream and riparian cover (30 - 70% over-hanging vegetation, boulders, and small woody debris), thereby establishing quality feeding habitat for various sport and forage fish species. Because of the lack of deep pools within the study area, it is not likely that this section of Conn Creek provides a significant amount of over-wintering habitat. However, the abundance of deep pools downstream near the confluence with the Athabasca River could provide suitable over-wintering habitat for fish

Northern Pike and Burbot, two species noted within Conn Creek and the Athabasca River, are relatively weak swimmers and require special consideration when incorporating fish passage into crossing designs. Both are classified as Anguilliform swimmers with sustained swimming speeds of 0.2 m/s and burst speeds of up to 0.75m/s for a distance of 10 m [3]. The limited swimming capacity of these two fish species, combined with limited regulatory or client support for measures such as baffles and rip-rap within culverts created unique challenges for the Conn Creek design. Additional challenges included the overall required length of the new crossing, need for adequate lighting, historic alteration of natural flow levels by the removal of upstream meander sections, constructability, economics, and project timing. The challenge was to provide an agreeable solution that would support fish passage in a safe and economical manner while satisfying the regulatory agencies and client.

Conceptual Alternatives

Channel Realignment

The existing structure was placed on an 11.2 degree skew to Hwy 63. The proposed alternatives concentrated on maintaining this alignment for the new structure as it is the only option that fits into the conceptual construction staging. The construction has to be staged to maintain traffic. Our staging plan required that the east half of the culvert be completed before the winter of 2009-10 to accommodate the new oversized load route.

A structure could be placed square in a location north of the existing culvert to slightly reduce the required length and reduce the risk of accommodating water throughout the construction of each stage. However, to accommodate staged construction, this would require a temporary structure to be built at the existing crossing. In order to avoid an open cut to the road to remove the existing culvert, it would likely have to be plugged with a controlled low strength material (CLSM), which would add substantially to the cost and negatively impact the schedule.

Providing a new location for the channel in combination with lengthening the existing channel would help reduce the structure profile and hence the velocities through the structure. This alternative was not evaluated in detail as there are two major gas pipelines and a sanitary force main on the downstream side of the site, and the upstream side has large embankments that would have to be cut. The original alignment of the channel prior to the twinning and current culvert installation is now covered by the footprint of the highway.

Culvert Repair and Extension

This option is to install 3600mm CSP liner in the existing culvert. The gap between the two culverts will be filled with low strength concrete. For the extension portion, new 3600 mm SPCSP culvert will be installed and connected to the CSP liner. Daylights will be installed at the medians to assist fish passing. Liner will extend the culvert service life by 45 years, the same as the design life of a new SPCSP culvert. Hydraulic modeling indicates that the upstream water level could rise by 0.3m during peak flow after liners are installed.

Culvert Replacement with Open Bottom Arch

This option is to replace the existing culvert with a 6000 mm SPCSP arch. Geotechnical investigation indicates that the bedrock at this site is quite shallow. A spread footing could be sufficient to support the arch culvert; however, AT best practice guidelines suggest that all bridge substructures be supported on pile foundations. As such this option significantly increases the construction cost and time when compared to the liner option.

Since the proximity to the limestone bedrock limits the ability to depress the culvert inlets, flow velocities through the culvert can only be reduced to match the existing channel velocities by widening the culvert opening at the streambed levels. While this approach may allow the passage of fish through the proposed culvert, the steep slope of the upstream reach will still result in high flow velocities that will affect the migration of fish further upstream.

Regulatory Discussions

After submitting the conceptual alternatives, the design team met with representatives from DFO to discuss concerns and potential compensation measures for the proposed rehabilitation and extension of the Conn Creek culvert. Based on these discussions, it became clear that the major obstacle for approval was that the existing culvert was viewed as a barrier to fish passage due to the excessive length, lack of lighting, and potential for high velocities. Following these discussions, design efforts focused on securing a viable solution that supports fish passage. It should also be noted that removal of an existing barrier to fish passage can be viewed as a fisheries compensation measure.

Stream Simulation

The hydraulic analysis of the existing channel indicated existing velocities exceeded the swimming abilities of the design fish (Northern Pike and Burbot) [3, 4]. Unfortunately, designing structures with low enough velocities to enable fish passage for the design fish species would make them susceptible to silting and icing. Another constraint was that changing the profile of a structure at this site was not practical due to the close proximity of the bedrock and our inability to lengthen the channel due to utilities downstream and large valley walls upstream. One potential option to increase roughness and reduce flows was the use of artificial substrate holder or baffles. Unfortunately, regulatory and maintenance issues eliminated this option.

The next option examined by the design team was increasing the opening of the culvert. The initial culvert installation in 1981 removed and straightened a significant portion of the upstream channel, producing an unnaturally high velocity environment at the existing crossing. Hydraulic modeling revealed that even an 11.8 m span open bottom arch could not provide adequate low velocities for fish passage. However, at this span length the flow velocity within the culvert can be effectively reduced to match the downstream channel velocity. To enable fish passage, the streambed within the culvert was simulated with the downstream channel natural streambed which has cobble/boulder substrate lining the channel.

Stream simulation creates natural stream processes within a culvert. Sediment transport, fish passage, flood and debris conveyances within the culvert are intended to function as they would in a natural channel. The main objective was to provide means for reducing flow velocities, with secondary objectives of providing velocity refuge, fish habitat, and ease of constructability: in essence, providing a functional ecological interpretation of ‘roughness’. There are several approaches to crossing design and fish passage evaluation [5-8]. The main focus used for this crossing was engineering, based on modeling of the roughness provided by features deployed to enhance habitat and assist with fish passage. Several in-channel design features (j-hooks, v-weirs, scour pools, boulder clusters, etc.) were initially selected that provided potential velocity refuge or resting areas. These were coupled with overall channel length features such as low flow channels, substrate types and sizing, and water depths. Many of these features, along with applicable design considerations, can be found in various stream restoration and culvert design publications noted above. During the design process, features were selected based on performance in reducing stream velocities, durability, ease of future maintenance, and constructability. Selected design features were assessed for overall roughness, with the final design being selected once all key attributes were addressed.

The main features of the final channel design included a series of v-weirs to extend channel length, a series of boulder clusters to provide velocity refuge at length increments within the swimming capacity of the target fish species, a central resting pool area, and a central channel to focus waters and ensure passage under low flow conditions. Elements are repeated in sequence within the new channel at intervals that support target fish species passage (**Figure 7**). In addition to the overall goal of enabling passage, the design features also provide a diversity of habitats including riffles, runs, meanders, and a pool, which are indicative of the natural channels found upstream and downstream of the crossing. Other benefits of the design are constructability and enhanced lighting.

Several other options such a j-hooks and tiered pools were explored, but many of these required specialized skills for proper placement and were potentially susceptible to failure given the high flow rates possible at this crossing. Inadequate lighting was viewed as a potential impediment to fish passage in long culverts. The larger openings of the arch system allow for a greater penetration of light, thereby reducing this effect. Overall, the arch system and designed stream channel provided the best option for supporting fish passage for this component of the overall project.

DFO Approval

The approval process for this crossing required buy-in from two main parties: the proponent and the regulators. In a simplified context this usually comes down to economics and regulatory directives. As mentioned earlier, regulatory concerns centered on fish passage issues and a preference for a bridge. Proponent concerns centered on economics and timing, as the overall project was well underway when this crossing was being designed and reviewed. Although several options other than a bridge were presented to regulatory authorities, the arch option was viewed as the only viable alternative. Following several additional reviews of all the options with respect to their varying economics and ability to secure approval in the very short time frame required to keep current project works on schedule, the proponent gave approval to present the open bottom arch with simulated streambed to the regulators. Approval for the arch option, without the need for compensation, was obtained shortly thereafter following acceptance by the proponent to conduct a water velocity and fish passage survey upon completion of project works.

Fish and Water Accommodation during Construction

In-stream timing constraints can protect fish species during critical life phases by limiting in-stream activities that could obstruct fish passage, cause direct lethal effects on fish, or reduce the overall productivity. Alberta Environment has designated restricted activity periods when in-stream construction is prohibited in Alberta streams accordingly. The restricted activity periods during which no in-stream work is permitted extends from April 16th to July 15th in Conn Creek. This restricted activity period was respected during construction planning. After foundation construction at the east end, a temporary streambed with J-Hook vanes was constructed in April 2011 and transitioned to the inlet of the existing culvert (**Figure 8**). After the east extension was completed Hwy 63 northbound traffic was routed to the high-load corridor by-pass. With the water well retained by the exiting culvert, foundation construction and culvert assembling proceeded well without any impact to fish and the stream. In the fall of 2011 the permanent streambed was constructed after the metal arch was assembled.

Lessons Learned

1. Regulatory approvals can sometimes resemble mediations. Securing timely approvals depends on understanding the parties involved and providing logical engineering solutions that satisfy their needs.

2. Providing solutions for engineering problems while meeting biological concerns requires dedicated and forward thinking individuals from both disciplines. We may not always speak the same language (i.e. Roughness vs. Velocity refuge), but we are both driven to find solutions.

3. The right solution is not necessarily the best; it is the one that satisfies the most objectives within the required time frame.

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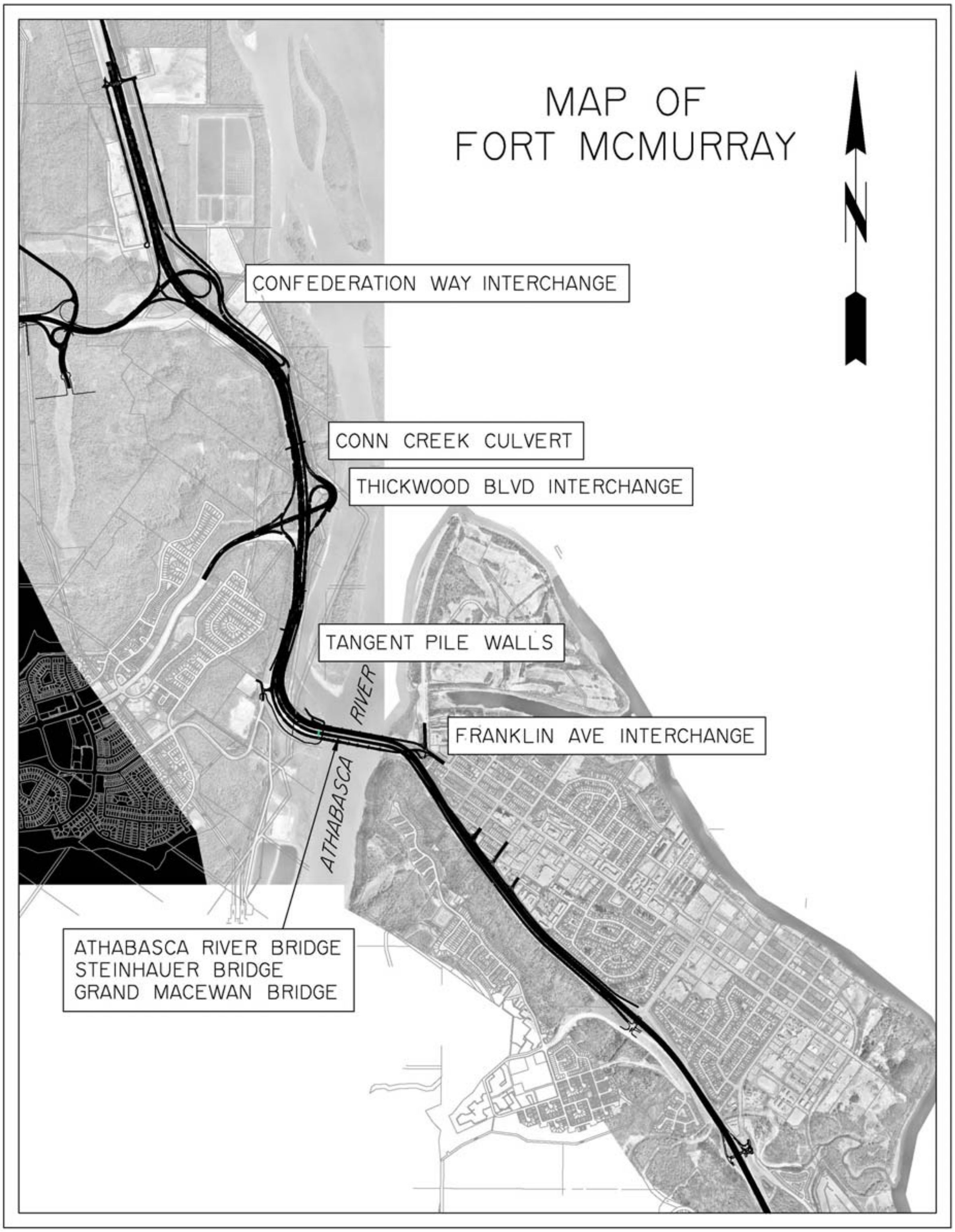

Figure 1: Highway 63:04 Upgrading Project Limit

Figure 2: Conn Creek 500m North of Thickwood Interchange

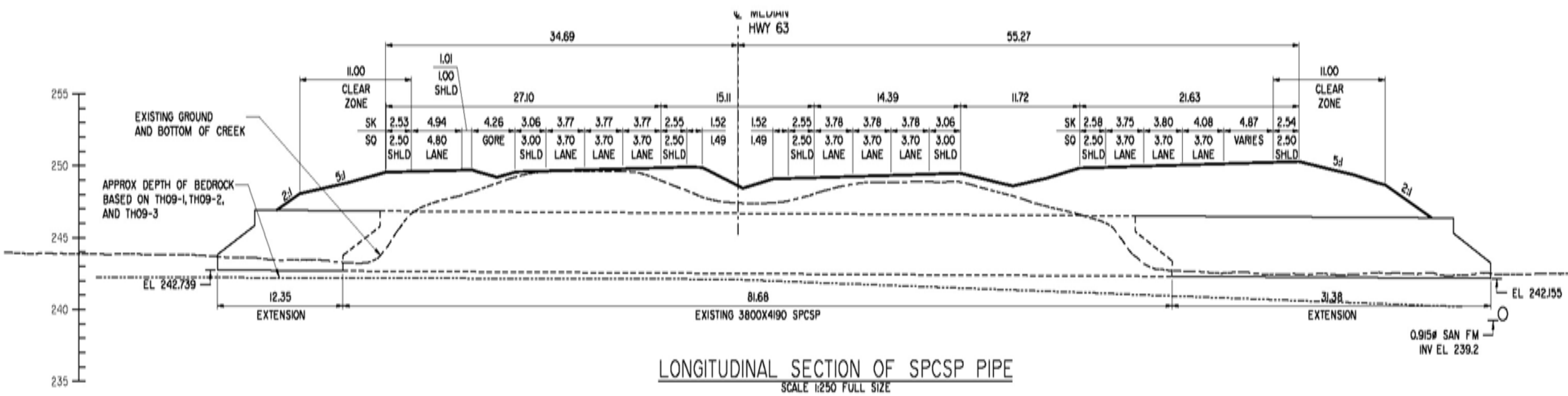

Figure 3: Proposed Highway 63 Cross Section at Conn Creek

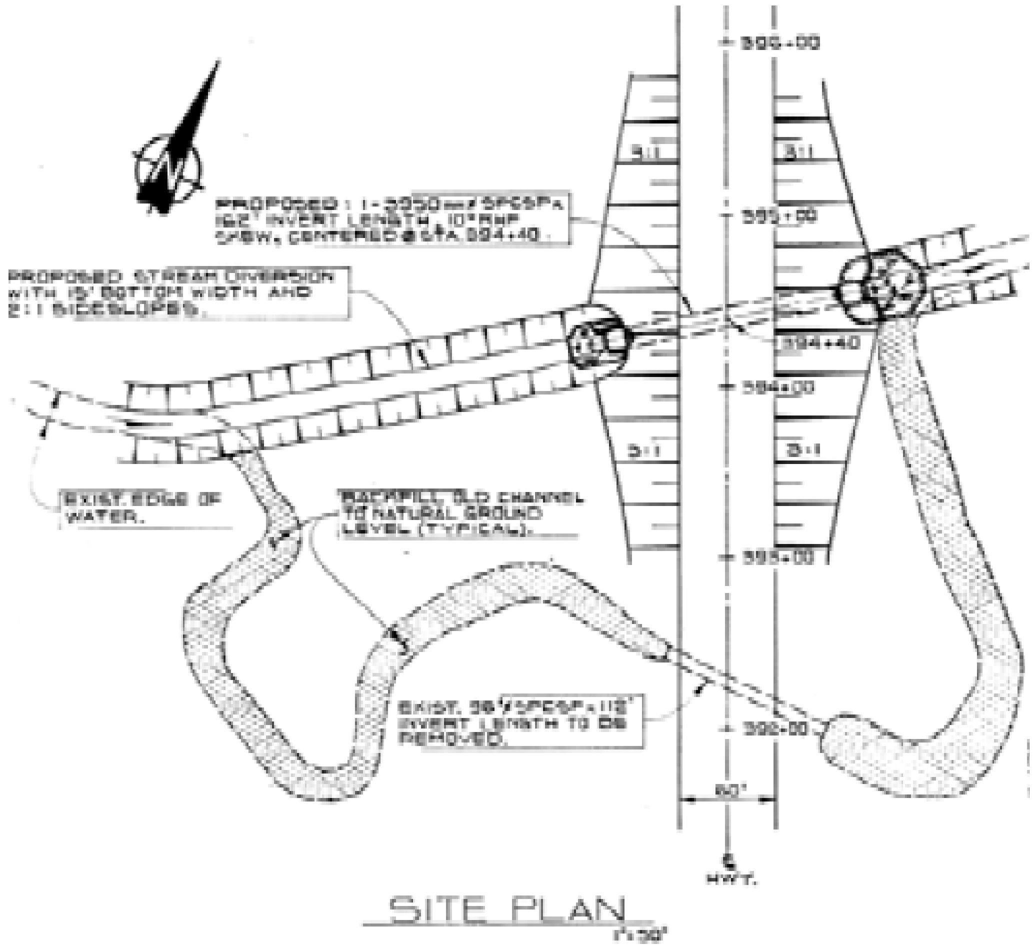

Figure 4: Conn Creek Realignment in 1981

Upstream

Downstream

Figure 5: Flow during Spring Runoff

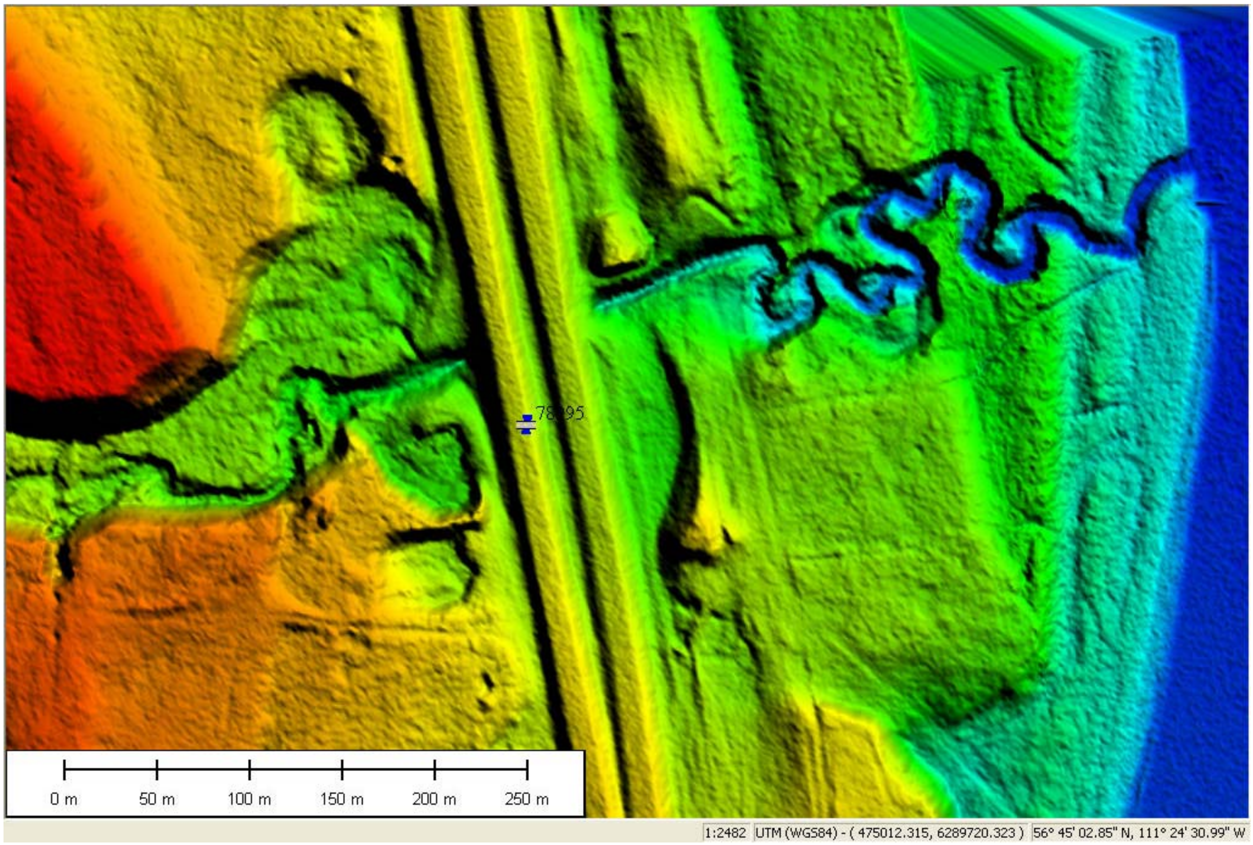

Figure 6: Topography at Conn Creek Crossing

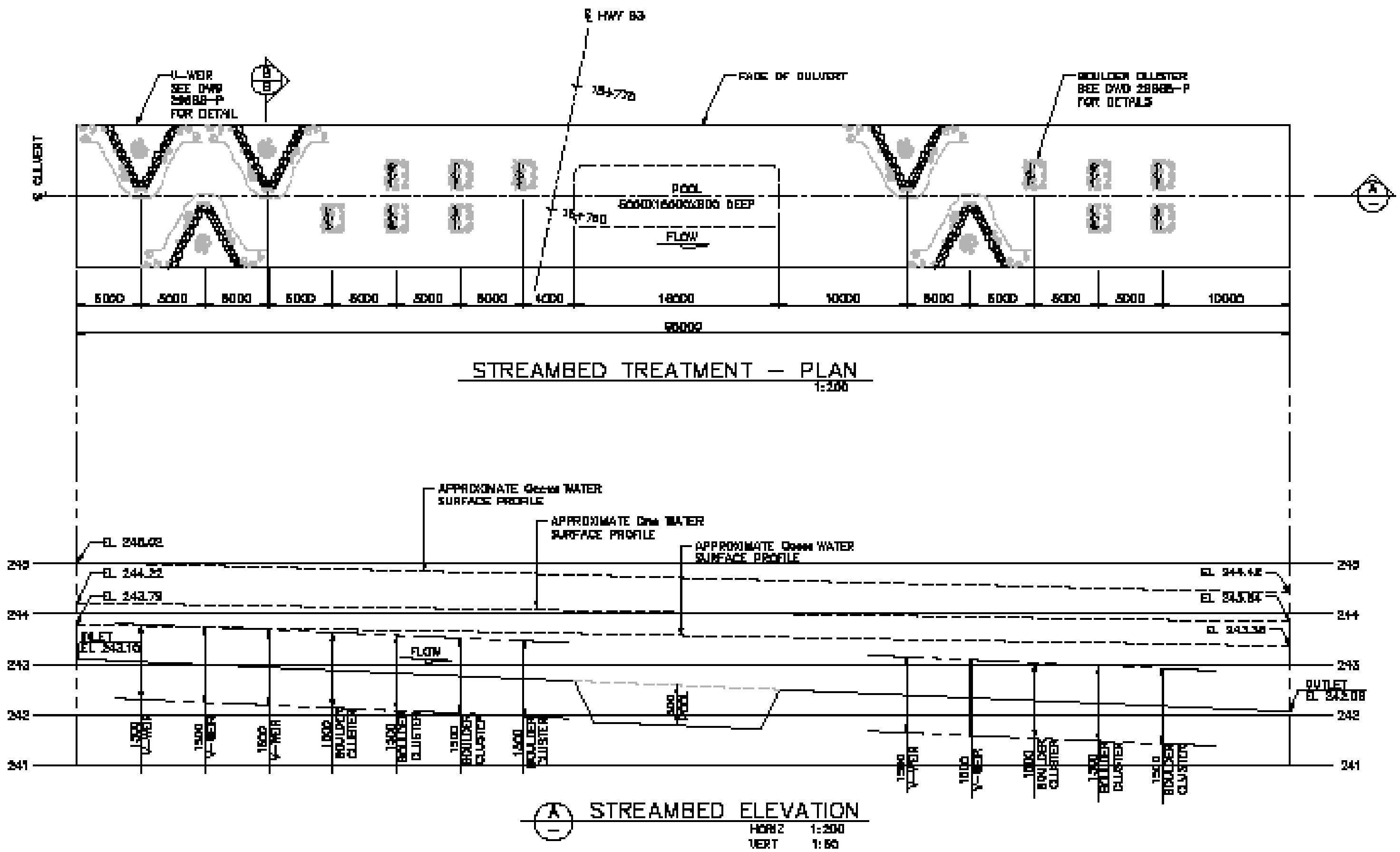

Figure 7: Stream Simulation Design within Culvert

Temporary Streambed with J-Hook Vanes

No Instream Work from April 16th to July 15th

Assembled Culvert Extension

Neat and Dry Bed for Foundation Construction

Construction under Core Lanes

Permanent Streambed under Construction

Figure 8: Fish and Water Accommodation during Construction