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Memorandum

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SUBJECT: PNW design guidelines for culverts in intertidal zones

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INTRODUCTION

The Chester Creek Fish Passage 30-percent design project (HDR and Inter-Fluve, 2001) includes construction of an open channel and flow conveyance structure through a railroad embankment to provide fish passage between Chester Creek habitats and the Knik Arm of Cook Inlet. The cost of the originally proposed trestle crossing exceeds available project funding. Therefore, an alternative is to be investigated that uses a large diameter culvert for the crossing. This culvert would be countersunk and partially filled with stream substrate materials to closely emulate a natural streambed.

The purpose of this memorandum is to summarize design approaches and methods for fish passage through culverts employed in the Pacific Northwest (PNW). These guidelines as they may apply to the Chester Creek project are discussed. An Internet search, literature review and interview were conducted in an effort to identify project examples.

FISH PASSAGE DESIGN IN THE PNW

A number of State guidelines and white papers regarding fish passage through culverts located in the PNW are available and included in the list of references. The reader is referred to these documents for specific design guidance for fish passage through culverts. These guidelines address stream and culvert profile, and hydraulic and bed material conditions necessary to facilitate salmonid fish passage. Little guidance for culverts in tidal areas is available.

In general, each State's guidelines closely follow that developed by the Washington Department of Fish and Wildlife (WDFW). The criteria presented in the guidelines are not absolute. It is recognized that the guidelines will not apply in every situation and that designs can be approved if adequate justification is provided (WDFW, 1999, pg 5).

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In Washington, adequate fish passage through culverts is based on criteria described in the Washington Administrative Code (WAC 220-110-070). The WAC describes two approaches to permanent culverts: a **no-slope option** and a **hydraulic design option**. A third option is also discussed; it is referred to as the **stream simulation option. The stream simulation option** is the construction of a channel within the culvert (WDFW, 1999, pg 5). Other states have similar guidelines and design methods. The stream simulation option is generally most preferred by regulatory biologists in Washington State (Bates, personal communication 12/2002).

These options, as they apply to Chester Creek, are discussed in more detail below.

No-slope option.

As stated in the WDFW guidelines, the no-slope option is defined by a culvert with:

- Width equal to or greater than the average streambed width at the elevation where the culvert intersects the streambed.
- A flat gradient along the stream bed within the culvert profile.
- A downstream culvert invert countersunk below the channel bed by a minimum of 20-percent of the culvert diameter or rise. (Diameter is 1.25 times the channel bed width.)
- Design considerations should evaluate the risk of upstream head cutting of the channel bed.
- Adequate flood capacity.

A reasonable upper limit for this option is for the condition where the natural channel slope (ft/ft) times culvert length (ft) does not exceed 20-percent of the culvert rise. The culvert is allowed to fill with sediment by natural stream process or is filled as part of construction.

Hydraulic design option.

The hydraulic design option is based on the swimming abilities of the target species and age class of fish. This option normally assumes that no substrate is initially placed in the bed of the culvert; bed material that later deposits adds conservatism to the design. Alternatively, bed material and/or baffles can be added as roughness to control the velocity to within fish passage criteria.

Culvert design provides hydraulic conditions that enable fish to swim through the pipe. From WDFW Table 1, average flow velocity criteria through a culvert 100- to 200-ft in length would need to be no greater than 3.0-fps for adult Pink and Chum salmon and no greater than 4.0-fps for adult Chinook, Coho, Sockeye and Steelhead for these fish to successfully pass the culvert.

The fish passage design high flow under which the flow velocity rules apply is based on enabling fish passage 90-percent of the time during the migration period for the target fish. This fish passage design high flow (Qfp) corresponds to the 10-percent exceedance flow. The 10-percent exceedance flow in Chester Creek estimated from USGS average daily flow records (USGS Gauge 15275100 Chester Creek At Arctic Boulevard at Anchorage, AK) is 33-cfs. The fish passage design high flow in the ADF&G/ADOT&PF Fish Pass MOA (2001, pg 9) is 0.4 times the 2-year peak flow or 45-cfs (0.4*112-cfs).

The hydraulic design option would direct the culvert designers to determine a culvert of sufficient size to convey 33- to 45-cfs with average velocities less than 3 feet per second. This option assumes that average velocities would be greatest during the 45-cfs flow and at low tide. Lower flows or higher tides would likely correspond to lower average velocities. This assumption is likely valid for the Chester Creek culvert.

Stream Simulation Option.

The Stream simulation option is intended to allow for some limited levels of natural stream processes within a culvert. Culverts are sized wider than the adjacent channel bank full width and fill material is placed in the bed of the culvert to mimic a stream channel thus creating instream conditions that promote juvenile fish passage. It is believed that the natural bed assists fish passage by providing a great variety of potential migration paths through the diversity of the natural bed.

Stream simulation is the preferred alternative for steep channels or long culverts. Current guidelines for suitable sites include channel widths of 20-ft or less and channel slopes no greater than 6-percent. Although these guidelines will likely be adjusted as the method is improved. In practice culverts have been constructed up to 36 feet in width and to slopes of 15% (Bates, personal communication, 12/2002).

The stream simulation option is a relatively new design method. Few installations have been in place for sufficient time period to be tested by stream flows. With time, the design guidance may change as more performance monitoring data become available. Therefore, there is some risk associated with this method. However, engineering design work can be used to predict forces acting on placed substrates within the culvert. These engineering methods would strive to design the substrate mixture size to remain stable during a high structural design discharge.

The characteristics of adjacent stream reaches are used to determine the size, slope and bed material within the pipe. Following analysis, native or engineered bed material may be used for culvert fill. The gradation of fill placed in the bed of the culvert is designed to contain fines to limit excessive subsurface flows that could result in a de-watered channel segment during low flow periods.

Culvert type is largely a matter of preference or material availability. Round culverts will have a greater depth of fill than a pipe arch. The width of the bed created in the culvert is twenty percent wider than the stream channel bank full width plus an additional 2-ft. Culvert diameters selected with these criteria are then filled to a depth of 30- to 50-percent of the culvert rise.

Tidal Considerations.

The WDFW guidelines briefly discusses culverts in tidal conditions:

> In tidally controlled situations, independent analyses of tidal influence and stream flows are necessary. For the tidal data, the hydraulic criteria discussed under the section on hydraulic design should be complied with at least six daylight hours on 90-percent of the days during the migration season. These criteria may apply to culverts and tide gates (WDFW, 1999, pg 16).

These comments are intended for retrofit or replacement culverts; criteria for new culverts normally require passage at all tidal elevations. Tidal passage design considerations were not located in other Agency's guidelines or the literature sources searched.

FISH SWIMMING BEHAVIORS

The referenced literature was searched for information on fish swimming behaviors. In addition, the American Fisheries and Canadian Journal of Fisheries Webpages were searched for relevant journal articles. In particular, information of depths which salmon prefer to use were of interest. The only specific swimming behavior information identified was for fish at dam fishways and locks (Bell, 1991). Bell found that:

- Eighty-percent of fish (no indication of species) position themselves in fish locks at depths between 3- and 6-ft (pg 33.1).
- Adult fish (no indication of species) approaching the base of a dam or obstruction are within the top 12-feet, with the most between the 2- and 3-ft depth levels. (pg 34.2)
- Orifices with darkened backgrounds are not entered by the fish as readily as those with the backgrounds lighted (either naturally or artificially). The light source may be by penetration through the water from either downstream or above the orifice. Lighting above the orifice, under the natural conditions of daylight, produces better and longer entrance attraction. (pg 34.2)

National Marine Fisheries Service culvert passage guidelines state that culverts greater than 150 long require a minimum diameter of six feet. Culverts less than 10 feet in diameter and greater than 150 feet long require artificial lighting every

75 feet. This can be achieved with a vertical riser that daylights at the top of the culvert (NMFS, Portland OR March 1, 1996).

Water Quality

Fish attraction and adaptation to changing water chemistry at the fresh water – saline water interface (e.g. temperature and salinity) was researched. No specific data or research publications were identified that discuss the attraction or residence time of fish at this interface. The time spent by fish within this transition zone is poorly researched but based on laboratory experiments it is reasonable to assume that adult and juvenile salmonids could transit the saline interface in a matter of days (see Piper et. al. 1989).

Culvert Fish Passage Feasibility

Bridges that span the entire stream channel and floodplain are always better than culverts for fish passage and stream function because they minimize any influence a crossing has on geomorphic and biological function by reducing potential change in local hydraulics. In some cases the expense or construction timeframe to build a bridge exceeds the available project funding or cost/benefit. In these cases either a new culvert or retrofitting an existing culvert is the next best option.

Due to construction timeframes and cost of re-routing the train track at the Chester Creek crossing, a passable culvert emulating a natural stream bottom is proposed.

Replacement culverts that emulate the natural bankfull dimensions as close as possible are better than those that impinge on those dimensions. Culvert widths similar to bankfull width will maintain natural stream bottom substrate and will have hydraulic conditions similar to the natural stream. Hydraulic analysis is required to size culvert material if the culvert impinges on natural bankfull widths or the design calls for substrate to remain immobile at flood flows that have naturally wider stream and active floodplain cross section than exist in the new culvert, as is the case at Chester Creek.

Many culverts have been replaced that emulate natural channels in Washington and Oregon. These function as well as a bridge would regarding upstream fish passage. Through proper design and implementation this can be achieved at Chester Creek. The Washington State *Fish Passage Design at Road Culverts* and computer software programs such as FishXing are two sources/methods to base and check design proposals to insure fish passage.

CULVERT ISSUES APPLICABLE TO CHESTER CREEK:

The proposed pipe would be large diameter (14- to 18-ft diameter) and would be filled to a depth of 3-ft with placed stream substrate material as used along the proposed constructed channel. The streambed material and cross section will mimic the upstream constructed channel as closely as possible within site constraints. For an 18-ft diameter culvert filled to a depth of 3-ft the surface width of substrate material would be about 13.4-ft.

PNW design method. PNW design guideline methods as they may apply to the Chester Creek would primarily be a roughened channel designed by the hydraulic design option.

Technically, the stream simulation option (where a natural bed is simulated in width, slope and bed) would only apply if the width is at least 1.2 times the natural bed plus 2 feet. The natural streambed in closest proximity to the site is located a distance upstream above the Westchester Lagoon. Characteristics of the upstream native streambed were not used. The approach taken for the proposed Chester Creek culvert is the construction of a roughened channel, which should be analyzed with the hydraulic method rather than as stream simulation. However, the bed of the proposed culvert would be designed to mimic natural streambed conditions as closely as possible within the specific site constraints.

PNW guidelines for roughened channels were developed primarily for non-tidal flows. At higher tide elevations, the culvert would become backwatered causing lower water velocities within the pipe. Boundary layer zone along the substrate and corrugations along the pipe walls and diversity of migration paths would provide additional low velocity zones for passage. Flow velocities would be checked during modeling to verify that they are passable for the target fish. Hydraulic conditions through the pipe would be used to size a stable stream substrate to be placed in the bottom of the culvert.

Fish attraction. ADF&G noted that returning salmon would benefit from being able to find the Chester Creek channel at high tide (MOA DPW, 1996). No specific literature was identified that addresses fish attraction or ability of fish to locate natal streams in estuaries. However, considering the discharge of flow and the relative conveyance area of the historic estuary, a narrow bridge or culvert would not dissipate velocities or dilute water quality constituents to the same degree that a wide bridge span or the historic estuary might. With this hydraulic condition in mind, it is reasonable to assume that returning fish searching for the chemical signature of Chester Creek would receive a fairly strong signature at the downstream pipe location regardless of tidal stage.

Culvert submergence. ADF&G recommended that fish access be provided at mean high tide (MHT), or elevation 29-ft mean lower low water (MLLW). The crown of the proposed culvert at the seaward end would be at elevation 30.3-ft, MLLW for an 18-ft diameter pipe. This elevation is above the MHT mark and satisfies ADFG's recommendation. Based on Bell's observations, that salmon swim in fishways at depths between 3- and 6-ft, it can be extrapolated that fish would be using the 23-ft, MLLW to 26-ft, MLLW zone in their migratory quest for passage through the new culvert. Fish swimming at this elevation during MHT would approach the culvert opening for a pipe as small as 14-ft in diameter with an outlet crown elevation of 26.3-ft, MLLW.

No published data was located that indicated whether fish would or would not pass a submerged pipe. (Although there are anecdotal reports of salmon successfully passing continual submerged culverts in the PNW. No information on length of delay at these culverts is available.) Should fish refuse to pass the Chester Creek culvert during submerged conditions, migration delay would be based on duration of submergence. Calculations by HDR indicate that 18-, 16- and 14-ft diameter pipes would be submerged by tides 2-, 8- and 16-percent of the time, respectively. The WDFW recommendation for intertidal culvert passage is that hydraulic criteria are met at least six daylight hours on 90-percent of the days during the migration period. Upstream migration along Chester Creek occurs from May through September. During this migration season, the shortest sunrise to sunset duration being slightly longer than 13-hours or slightly longer than one complete tide cycle. Thus, a 6-hour non-submergence duration during daylight hours would roughly correspond to a 50-percent tide exceedance. Therefore, the 14-, 16- and 18-ft diameter culverts would all satisfy the WDFW guideline.

This project was discussed with a WDFW fish passage engineer in the context of Washington State fish passage guidelines. It was the opinion of the engineer that for a restoration project of this type where one could expect to see marked improvement of fish passage in the upstream and downstream directions and improvement of salinity and temperature transition conditions, submergence of a pipe for 1- to 2-hours per day would not generally prevent the project from being implemented. One key consideration in this opinion is that project cost savings might be applied to other restoration projects. Cost considerations and priorities are, of course, regional issues (Bates, personal communication, 12/2002)

Intertidal zone function. Providing adequate conveyance for exchange of flood and ebb tide flows will minimize impacts to the intertidal zone upstream of the railroad embankment. The large diameter of the proposed Chester Creek culvert combined with the relatively small inter-tidal storage volume will likely provide free exchange of water during flood and ebb tides and water levels to equalize on both sides of the crossing. Unsteady flow modeling would be required to quantitatively predict flow exchange, detention and velocities during flood and ebb tides.

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