TECHNICAL MEMORANDUM

Date: **20 November 2005**
From: **J. M. Colonell**
To: **Project file – Knik Arm hydrology**
Subject: **Flow velocities around bridge abutments**

1.0 Environmental Issue

Alternative 1 for the proposed Knik Arm Crossing (KAC) includes earthen approach embankments extending from opposite sides of Knik Arm to a maximum depth of –20 ft re: MLLW, thereby leaving a gap of approximately 8,200 ft which would be spanned by a pile-supported roadway. Concern has been expressed that the flow around the distal ends of these embankments would pose a barrier to passage of small fishes from one side of KAC to the other, due to (1) the overall increase in flow velocity produced by constriction of Knik Arm tidal flows to the 8,200-ft gap between the embankments, and (2) the acceleration of flows rounding the corners of the abutments.

All fluid flows are impeded in the vicinity of solid boundaries. The amount of impedance, or slowing, of the flow is a function of the amount of solid boundary in contact with the flow, called the "wetted perimeter," and the roughness of the boundary itself. Accordingly, flow past the distal ends of the earthen embankments of the KAC will be similarly impeded. Indeed, there will be a wedge-shaped volume of that flow, herein called the "boundary layer wedge," or BLW, within which flow velocities will be sufficiently impeded (i.e. lowered) such that the needs of juvenile fish for lower flow speeds to navigate their way past the embankments will be accommodated (Figure 1).

The BLW will expand and contract as tidal flow speeds wax and wane with the tidal cycle. Flow speeds will be maximum at mid-tide, both flood and ebb, and will be near-zero at flood and ebb slack water. Thus the BLW will have its minimum volume (i.e. minimum cross-sectional area) at mid-tide, an occurrence which will determine the volume of the flow cross-section within which flow speeds remain navigable for small fishes. The criterion for determining the size of the boundary layer wedge that is suitable for small fish passage is established by the maximum swimming speed that can be sustained by the fish species of concern.

2.0 Analysis

The question of whether flow over the abutment surface is sufficiently slowed by its roughness to accommodate the needs for juvenile fish passage can be addressed with the Manning equation, which has been used successfully for estimating velocities and flow rates in open channels for more than a century (e.g. see Vennard & Street 1975).

$$V = (1/N)\, R^{2/3}\, S^{1/2} \qquad \text{(Eqn. 1)}$$

In Equation (1), V = average flow velocity, N = Manning roughness coefficient, R = hydraulic radius, and S = water surface slope. The hydraulic radius R is defined as the flow cross-sectional area A divided by the wetted perimeter P, (i.e. R = A/P). Values of the roughness coefficient have been determined experimentally for numerous flow surfaces ranging from the smooth (e.g. finished concrete) to very rough (e.g. large cobbles), and are available in most hydraulic texts or handbooks (e.g., Blevins 1984).

Average velocity of flow over the abutment, hereafter referred to as "abutment flow," can be related to the average flow velocity in the main channel through the Manning equation. Letting V_1 = average velocity of abutment flow and V_2 = average velocity of flow in the adjacent main channel, the ratio of the average velocities is V_r, which can be expressed as the quotient of the Manning equations for the two flow cross-sections:

$$V_r = V_1 / V_2 = (1/N_r)\, R_r^{2/3}\, S_r^{1/2} \qquad \text{(Eqn. 2)}$$

In Equation (2) N_r, R_r, and S_r are, respectively, the ratios of Manning roughness coefficients, hydraulic radii, and water surface slopes in the BLW and adjacent main channel.

For the abutment flow, the flow cross-section is the triangular area with height H and width MH, such that $A_1=0.5MH^2$, in which M is the abutment side slope (1 vertical: M horizontal) and H is the water depth at the abutment toe. The wetted perimeter of the abutment flow is the side slope length, which is the hypotenuse of the flow cross-section, or $P_1 = \sqrt{[H^2+(HM)^2]}$, so the hydraulic radius R_1 is given by

$$R_1 = 0.5MH^2 / \sqrt{[H^2 + (HM)^2]} \qquad \text{(Eqn. 3)}$$

Within the main channel, the hydraulic radius is simply the depth H, (i.e. taken here as the depth of the channel adjacent to the abutment.

Assuming water surface slopes are equal (i.e. $S_r = 1$), it can be shown that

$$V_r = (1/N_r) * [0.5 \sqrt{(1/ (1 + 1/M^2))}]^{2/3} \qquad \text{(Eqn. 4)}$$

Using N_r as a parameter (ratio of abutment roughness to channel roughness), solutions of Equation 3 were obtained for a range of abutment slopes (M) as listed in Table 1.

Table 1. Ratio of average velocities (Abutment Flow: Main Channel Flow), as function of abutment side slope and roughness ratio

Roughness Ratio N_r (=N_1/N_2)	***Abutment Side Slope (M)***				
	2	**3**	**4**	**5**	**10**
1.0	0.585	0.608	0.617	0.622	0.628
1.5	0.390	0.405	0.411	0.414	0.418
2.0	**0.292**	**0.304**	**0.309**	**0.311**	**0.314**
2.5	0.234	0.243	0.247	0.249	0.251
3.0	0.195	0.203	0.206	0.207	0.209

As results indicate, the ratio of average flow velocities is a relatively weak function of abutment side slope, while being strongly influenced by the roughness ratio. Assuming conservatively that the roughness ratio will be at least 2.0, which implies that the abutment surface has a Manning roughness coefficient twice that of the adjacent Knik Arm seabed, and abutment side slopes of either 2:1 or 3:1, the velocity ratio will be about 0.3; that is, the average abutment flow velocity would be about 30% of the channel flow velocity. The next step is to determine the size of the Boundary Layer Wedge (BLW) within the abutment flow is sufficiently slowed accommodate the needs of migrating juvenile fish.

Hydrodynamic modeling[1] of maximum (spring tide) flows shows that, for both flood and ebb tides, there will be a narrowing of the flow as it passes between the embankments. To examine the flow detail near the abutments, the hydrodynamic model was run with a 15-m (49-ft) grid for maximum spring tide conditions to compute velocities corresponding to both ebb and flood tidal flows. As discussed in the main report and in Appendix III, ebb flows are faster than flood flows, but it is the latter that are of concern with regard to effects on juvenile fish because they are beginning their journeys southward into Cook Inlet.

Figures 2 and 3 show the flow details near the abutment corners. Both are quite similar, although the flow along the face of the east abutment (Fig. 2) appears to be slightly faster than that for the west abutment (Fig. 3), with a maximum speed of about 2 m/s (6.6 ft/s). According to Table 1, with N_r = 2, and side slope 1:2, average flow velocity over the abutment will be 1.9 ft/s (= 0.29 * 6.6 ft/s).

To estimate the horizontal width of the BLW, it is first necessary to determine the shape of the horizontal velocity profile. The total flow over the abutment is the product of the cross-sectional area and the average flow velocity. The maximum flow conditions illustrated by Figs. 2 and 3 occur at mid-tide, when the water depth is about 20 ft over the toe of the abutment. With a side slope of 1V: 2H, the horizontal dimension of the flow cross-section is 40 ft (i.e. 2 x depth). Accordingly, the discharge

$$Q = 1.9x(0.5x36x72) = 2{,}462\ ft^3/s$$

Conservation of mass (i.e. "continuity") requires that the integral of the velocity profile over the flow area is equal to the total discharge; i.e.,

$$Q = \int V(y)\, dA = 2{,}462\ ft^3/s \qquad (Eqn.\ 5)$$

in which V(y) is the horizontal variation of depth-averaged velocity over the abutment and dA is the area element. For a flow such as this, it is reasonable to expect that a "power law" profile will satisfy the requirements of continuity (Schlichting 1987). Using curve-fitting techniques, velocity profiles of the following form were tested:

$$V(y)/ V_m = A[1 - (y/L)]^{p} \qquad (Eqn.\ 6)$$

In Eqn. (6), V_m is the main channel velocity above the abutment toe, y is the horizontal distance coordinate, measured from the abutment toe (y=0) to the shoreline (y = L = 72 ft), A is a constant of proportionality, and p is the "power law" exponent that provides the best fit. The exponent p was found by integrating Eqn. (6) over the flow cross-section for various integral values of p, until the the ratio of depth-averaged velocities determined by the Manning equation was found; i.e. V_r = 0.29. With A = 1 and exponent p = 5, the integration resulted in a computed discharge of 2,530 ft³/s, which was considered to be

---

[1] See Hydrology and Hydraulics of Knik Arm, App. III (URS 2005c).

satisfactory agreement with Equation (5). Consequently, the horizontal depth-averaged velocity profile is given by

$$V(y) = 6.6\,[1 - (y/72)]^{5} \qquad \text{(Eqn. 7)}$$

from which depth-averaged velocity can be computed as a function of distance from the abutment toe (Table 2). Figure 4 is a graphical presentation of depth-averaged velocity over the abutment.

Table 2. Depth-Averaged Velocity and Water Depth vs Distance from Abutment Toe

	Distance (ft) from toe of abutment										
	0	7.2	14.4	21.6	28.8	36.0	43.2	50.4	57.6	64.8	72.0
Depth-Averaged Velocity (ft/s)	6.60	3.90	2.16	1.11	0.51	0.21	0.07	0.02	0.00	0.00	0.00
Depth (ft) at mid-tide	36.0	32.4	28.8	25.2	21.6	18.0	14.4	10.8	7.2	3.6	0

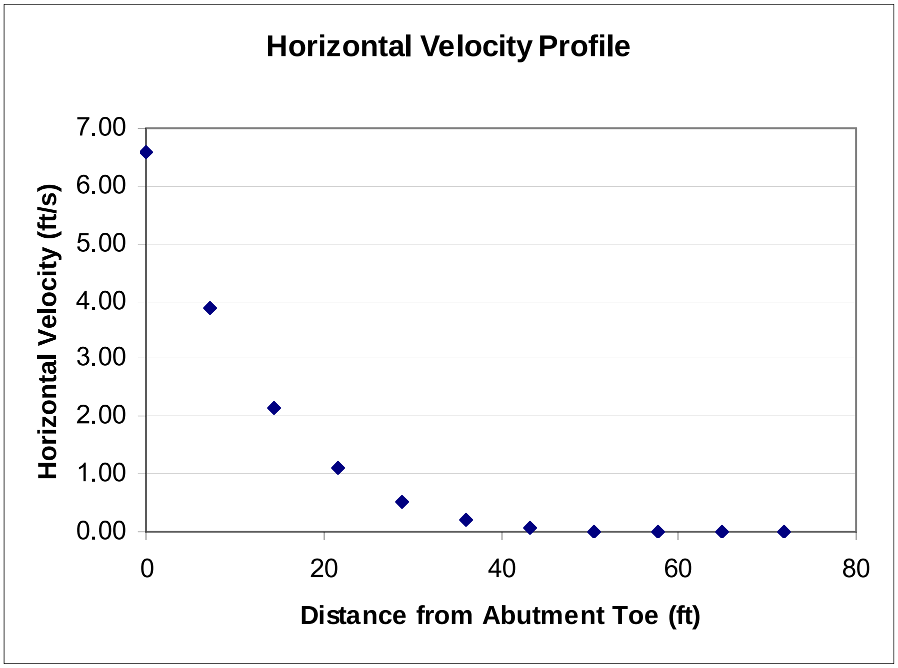

Figure 4. Depth-averaged velocity as function of distance from abutment toe

3.0 Results

The fishes of concern here are the several species of salmon that frequent Knik Arm and, specifically, salmonid fry. In tests of these species at the Fisheries Research

Institute (Smith and Carpenter 1987), a “critical velocity” was defined as the maximum speed that fry of a specific size could maintain for 15 minutes. The fry used in these experiments ranged in length from 25 mm to 40 mm (.08 – 0.13 feet). Temperature was also a parameter in these experiments. Results (at 10°C.) indicated that fry in this length range could sustain speeds of 4 – 5 times their length (per second) for 15 minutes. Taking the lower end of this range, it could be concluded that fry of 25-40 mm length can swim at speeds of 0.3-0.5 feet/s.

The preceding computations of flow over the abutment demonstrate that, even at maximum tidal flows (i.e., spring flood), there will be wedge-shaped zone adjacent to the abutment armor that is several feet thick within which the flow speed will be less than 0.5 ft/s. According to the computations presented above, this wedge-shaped zone will extend about 43 ft from the shoreline to a depth of about 22 ft (Figure 1).

4.0 Conclusion

Boundary layer flow computations indicate that there is an ample cross-section of low-speed flow through which the fry should be able to navigate comfortably. In any case, the fry would be able to “hold their own” against the current and would have opportunities for rest and shelter within the numerous crevices of the armor rock.

5.0 References

Blevins, R. D. 1984. Applied Fluid Dynamics Handbook. Van Nostrand Reinhold Company, Inc., New York. 558 p.

Schlichting, H. 1960. Boundary Layer Theory. McGraw-Hill Book Company, Inc., New York. 647 p.

Smith and Carpenter 1987. Salmonid Fry Swimming Stamina Data for Diversion Screen Criteria. Seattle, WA: Fisheries Research Institute, University of Washington.

Vennard, J. K., and R. L. Street. 1975. Elementary Fluid Mechanics, 5th Ed. John Wiley & Sons, Inc. New York. 740 p.