Velocity Distributions Impacts on Fish Passage at Culverts

Introduction

Assessment of flow velocity in a culvert is an important component of assessing the potential for fish passage. Velocities may need to be computed over a range of flow conditions that are likely during periods of fish passage need. Tools have been developed to accurately predict the longitudinal distribution of the mean (section-averaged) velocity for a given flow condition and culvert geometry. These tools account for flow profile changes along a culvert due to tailwater effects of culvert embedment.

Alberta Transportation (AT) has proposed a fish passage assessment methodology that compares the mean flow velocity in the pipe to that of the typical channel. Comparable mean velocities would suggest that a given culvert configuration would not be a velocity barrier to fish passage. In addition, culverts providing similar mean flow velocities to the channel at the most frequent flows should minimize the impact on overall river processes.

However, concerns have been expressed about the validity of the mean velocity being used to compare fish passage in channels and culverts. Culverts provide a length of constant section, profile, and alignment that in many cases will exceed that of a natural channel, and this may affect the availability of low velocity zones in the flow. In order to quantify this impact, a study has been undertaken to compare the distribution of flow velocity over a cross section between culverts and channels. Knowledge of the velocity distribution at culverts may also provide useful guidance in the application of fish swimming performance curves.

Methodology

Data on the distribution of flow velocity over a cross section for both culverts and open channels is available from several sources. Data on velocities within round corrugated metal pipes has been published based on field studies such as Katopodis et al (1978), Behlke et al (1991), Taylor and Love (2003), Lang et al (2004) and based on laboratory studies such as Barber and Downs (1996) and Ead et al (2000). Laboratory studies have the advantage of more control over flow conditions, but come with unavoidable scale effects. Additional data for embedded culverts has been published by House et al (2005) and Kehler (2009). Barber and Downs also evaluated a smooth wall (no corrugations) pipe.

A convenient source of open channel velocity distribution data covering a wide range of flow and channel geometry conditions is the gauging data collected by the Water Survey of Canada (WSC). Data from about 40 gaugings at sites across Alberta have been analysed.

In all cases, each data-set was processed into a table of percentage of flow area (%A) with mean velocity (v) for that percentage area as a ratio of section-averaged mean velocity (V). For data that was in the form of velocity contour plots at a cross section, the contours were digitized and the areas enclosed by each contour calculated (see Figure 1 and Figure 2). For data that was in the form of x,y,v data-sets, GIS tools were used to develop cumulative velocity histograms for the cross section. Culvert data was limited to sections with flow up to about half full, which is typical for fish passage conditions. In addition, the culvert data was limited to sections of fully developed flow, meaning that the data is not influenced by local effects such as contractions and expansions near the ends of the culvert. The %A and v/V data were compiled into separate databases for channels, culverts with granular substrate, corrugated metal culverts, and smooth wall culverts.

Analysis

Figure 3a, 3b, and 3c show plots of %A versus v/V for channels, culverts with granular substrate, and corrugated metal culverts respectively. Visual best fit lines with two slopes have been added to the plots. Figure 4 shows the best fit lines on the same plot, along with the one data-set for a smooth wall pipe. Summary data showing v/V for a range of %A likely of interest to fish passage is shown in Table 1.

%A	v/V			
	Smooth Pipe	Corr. Pipe	Substrate	Channel
10	0.45	0.20	0.15	0.12
20	0.6	0.40	0.3	0.24
30	0.7	0.60	0.45	0.36

Table 1 – velocity distribution - fish passage range

It is readily apparent from Figure 4 and Table 1 that there is a noticeable difference in the distribution of velocity for each case. As would be expected, natural channels do provide more diversity in the velocity distribution, with smaller v/V ratios at the same %A value. However, the difference between the natural channel data and the culverts with granular substrate data is relatively small, suggesting that roughness is the main factor in the difference in velocity distribution. This is confirmed when adding the corrugated pipes and smooth wall pipes to the comparison. The v/V ratios for a given %A rise as the roughness of the pipe decreases. Therefore, it is apparent that there is a double benefit to providing additional roughness to a pipe – mean velocities decrease, and the proportion of flow area with small fractions of the mean velocity increase. Of course, the impact of roughness will be most significant at locations where flow is close to normal flow conditions and clear of backwater influences such as due to culvert embedment.

It is also clear from Figure 4 and Table 1 that a substantial distribution of velocity is present at all pipes. Even the smooth wall pipes provide significant areas where the velocity is a fraction of the section-averaged mean velocity. If 20% of the flow area is sufficient to handle fish passage, then the fish would only have to swim against 40% of the mean velocity in a corrugated pipe.

Conclusion

A comparison between flow velocity distribution in culverts and open channels was undertaken, based on published data-sets. It is apparent that roughness is a significant factor in the variance in velocity distribution that was observed. An increase in roughness can increase the amount of area with flow velocity at a certain fraction of the section-averaged mean velocity. Conversely, an increase in roughness can decrease the flow velocity over a fixed percentage of the flow area. This is in addition to the reduction in section-averaged mean velocity due to an increase in roughness. These observations suggest that properly placed granular substrates may significantly enhance the ability of fish to find velocities that they can swim against. The most effective locations for such substrates would be at the upstream portion of culverts on high velocity streams where the culvert the backwater effect from culvert embedment has been minimized.

Although it is clear that natural channels do provide larger areas of low velocity than corrugated pipes, the velocity distribution at corrugated pipes is still significant. Typically, 20% of the flow area at corrugated pipes will have mean velocities less than 40% of the section-averaged mean velocity. By comparison, slightly more than 30% of the flow area in a natural channel would have velocities in this range. Therefore, the assessment of fish passage based on a comparison of mean velocities between the culvert and the channel appears to be a reasonable approach. If, however, theoretical fish swimming performance curves are to be used, the comparison should be based on a fraction of the mean velocity due to the provision of large areas with velocities much lower than the section-averaged mean velocity.

References

Barber, M.E., and Downs, R.C., 1996. “Investigation of Culvert Hydraulics Related to Juvenile Fish Passage”. Washington State DOT Technical Report No. WA-RD 388.2.

Behlke, C., Kane, D.L., McLean, R.F., and Travis, M.D., 1991. “Fundamentals of Culvert Design for Passage of Weak-Swimming Fish”. FHWA Research Report No. FHWA-AK-RD-90-10.

Ead, S.A., Rajaratnam, N., Katopodis, C., and Ade, F., 2000. “Turbulent Open-Channel Flow in Circular Corrugated Culverts”. Journal of Hydraulic Engineering, Vol. 126, No. 10, p750.

House, M.R., Marvin, R.P., White, D., 2005. “Velocity Distributions in Streambed Simulation Culverts used for Fish Passage”. Journal of the American Water Resources Association, 41(1):209-217.

Katopodis, C., Robinson, P.R., and Sutherland, B.G., 1978. "A study of model and prototype culvert baffling." Canadian Fisheries and Marine Service, Technical Report 828

Kehler, N.J., 2009. “Hydraulic Characteristics of Fully Developed Flow in Circular Culverts”. Master of Sciences Thesis, Department of Civil Engineering, University of Manitoba, Winnipeg, Manitoba.

Lang, M., Love, M., and Trush, W., 2004. “Improving Stream Crossings for Fish Passage”. National Marine Fisheries Service Contract No. 50ABNF800082.

Taylor, R, and Love, M., 2003. Fish Passage Evaluation at Stream Crossings. Part IX of California Salmonid Stream Habitat Restoration Manual. California Dept. of Fish and Game.

WSC Data – gauging records, Alberta Region, Water Survey of Canada, Environment Canada

Figure 1 – Sample Culvert Calculation (based on data from Behlke, 1991)

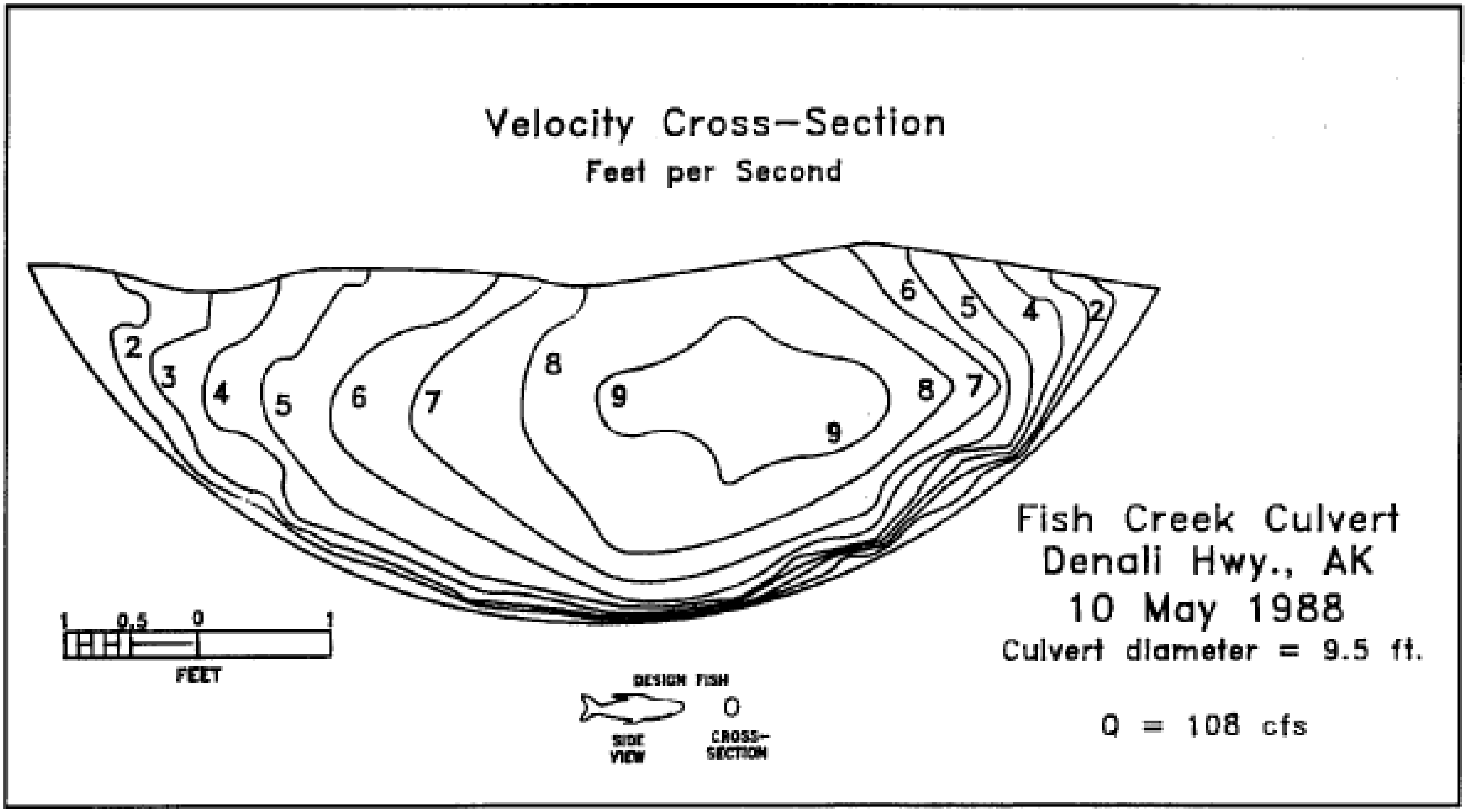

Figure 2 – Sample Channel Calculation (WSC data)

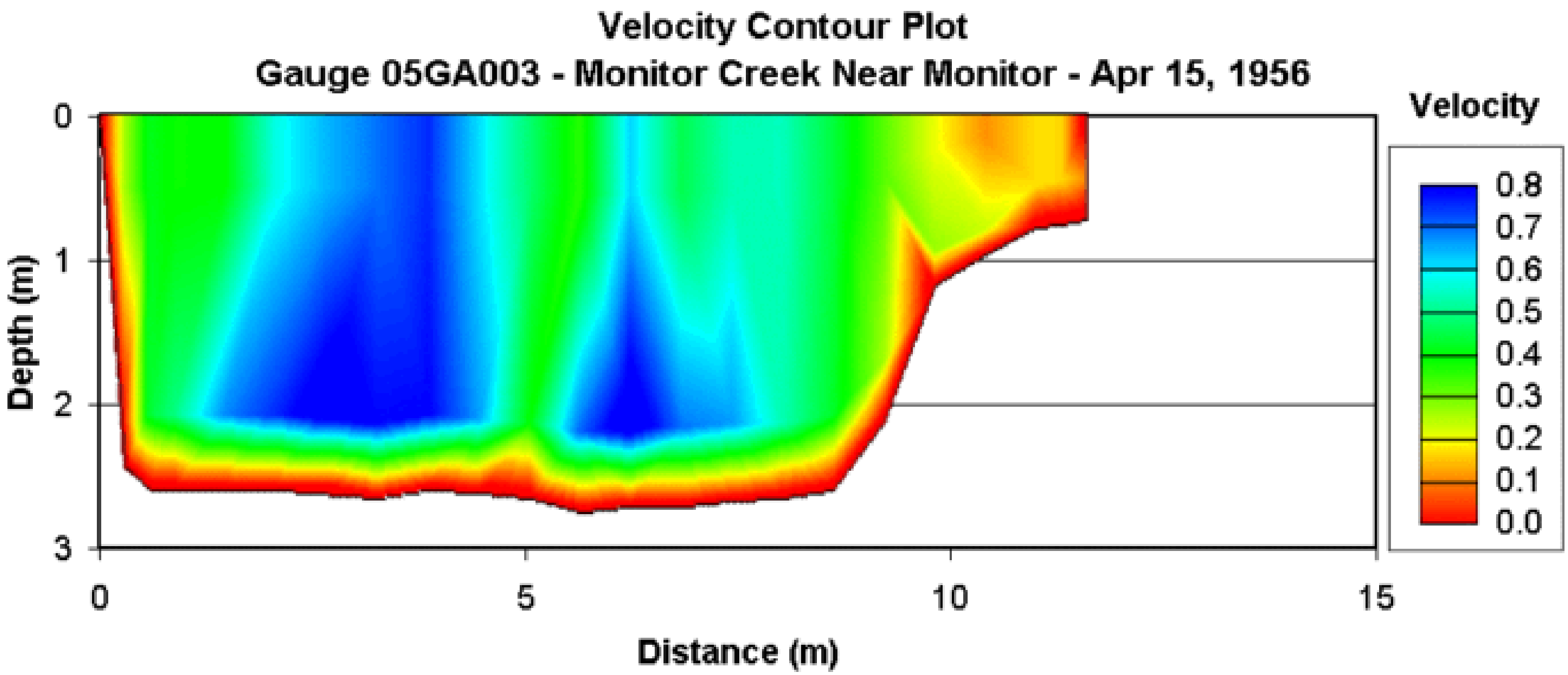

Figure 3a – Velocity Distribution - Channels

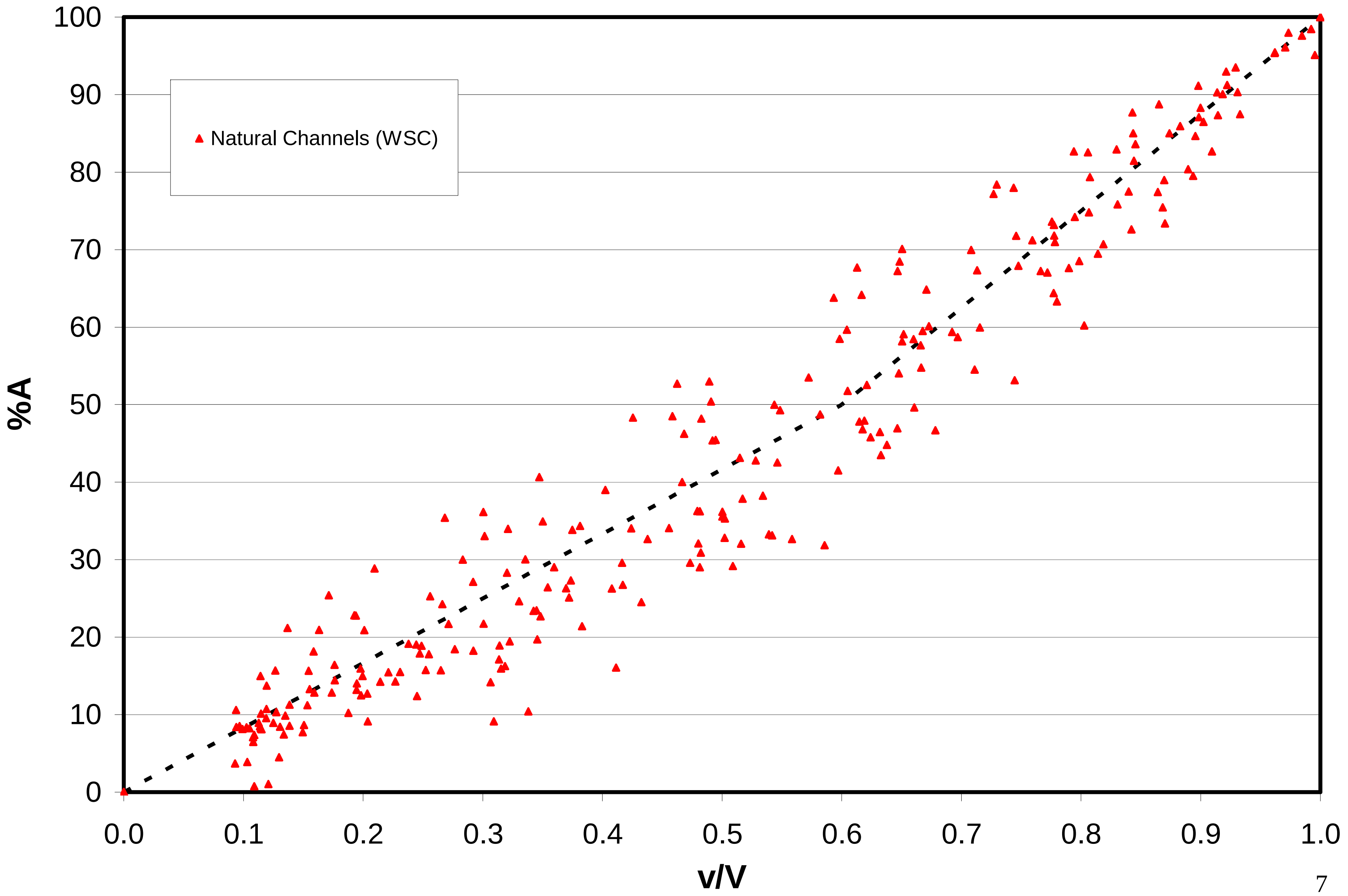

Figure 3b – Velocity Distribution - Culverts with Granular Substrate

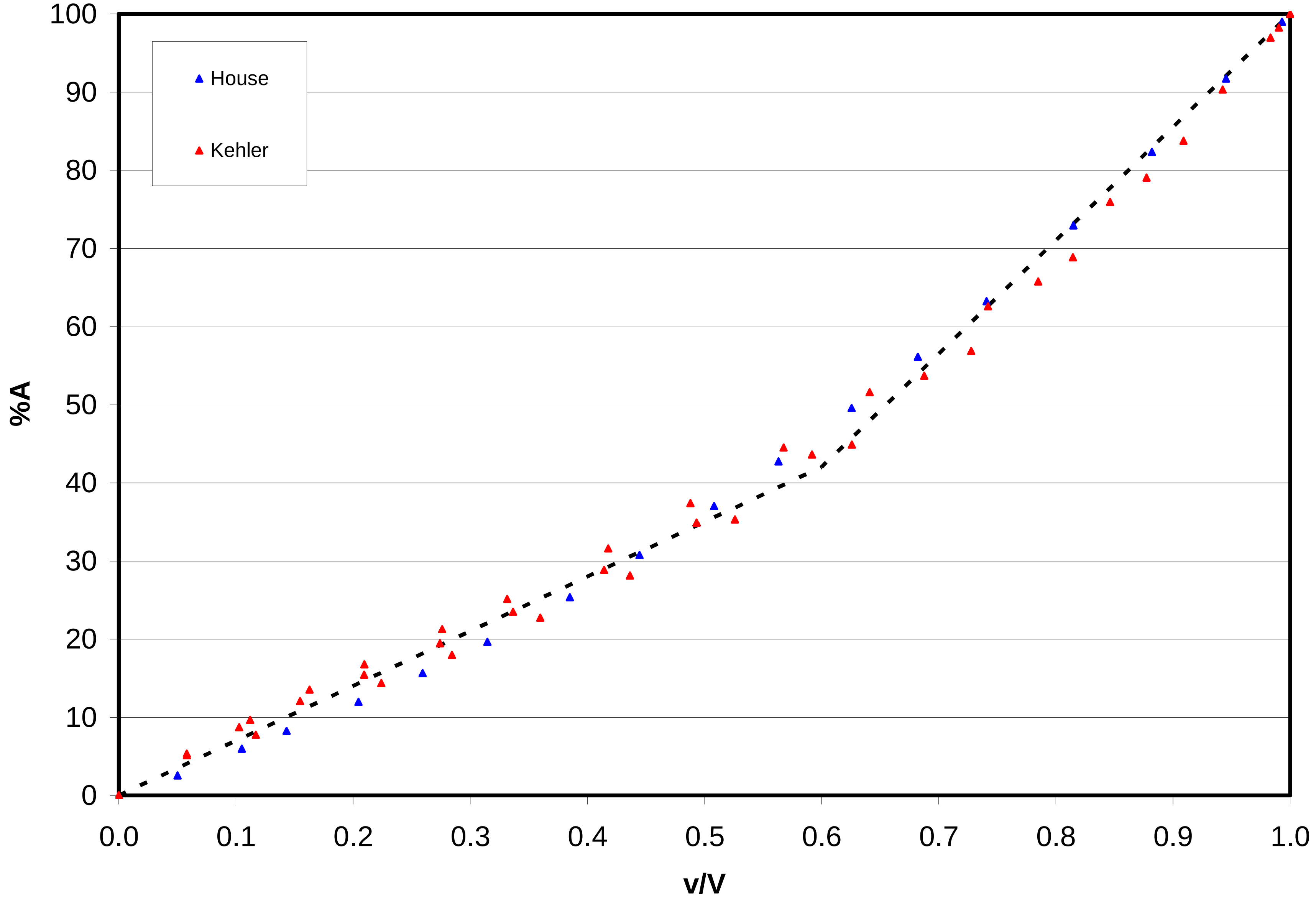

Figure 3c – Velocity Distribution – Corrugated Metal Culverts

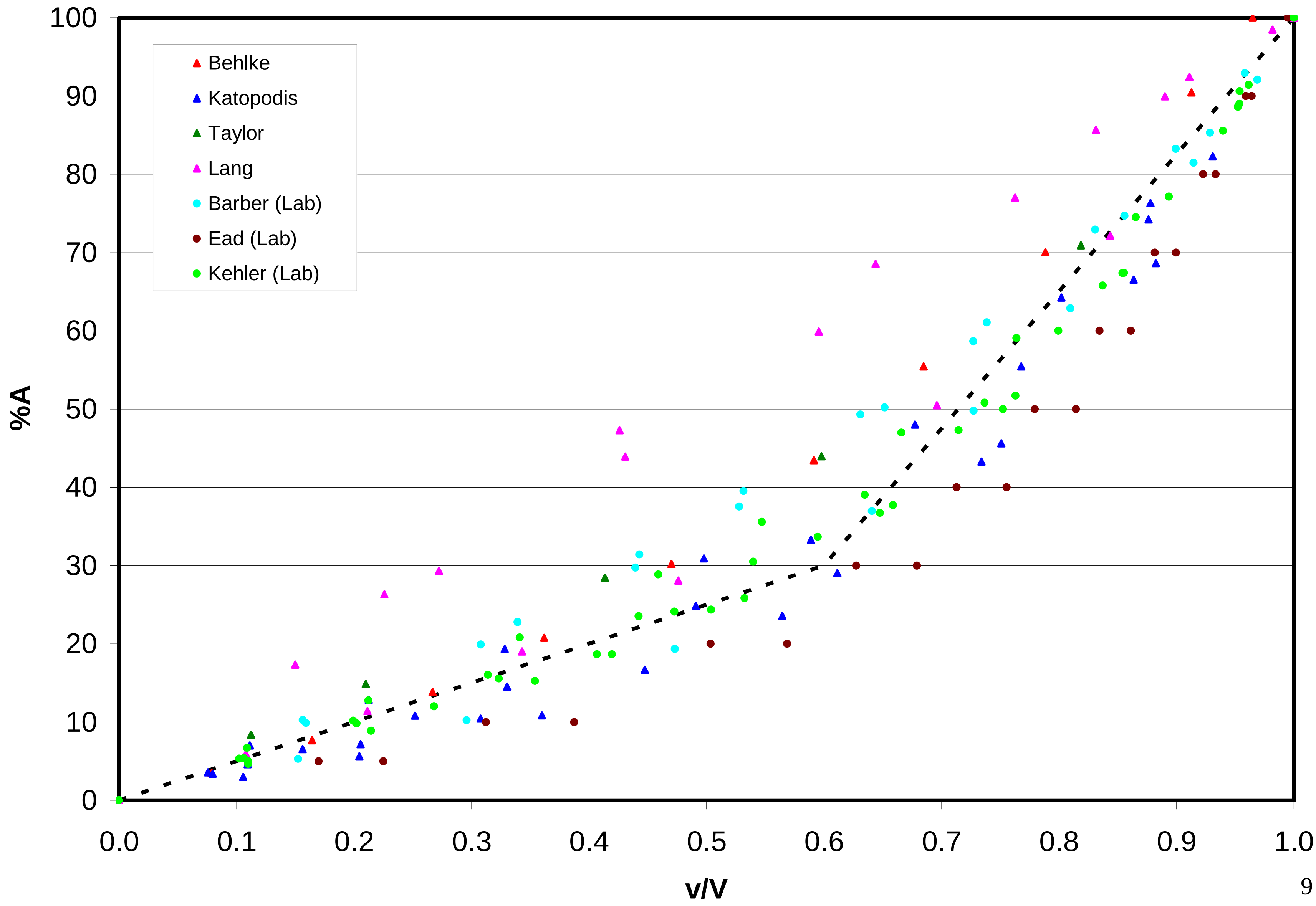

Figure 4 – Velocity Distribution Comparison