Full Length Research Paper

Improvement of flow velocity formula for nature-like fishways

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A dam is a useful structure for human society, but does harm to wildlife such as migratory fish. Thus, in order to conserve fish habitat, fish passage can be constructed. For designing a nature-like fishway, through-flow velocity, which is defined as the average velocity over water flow through rock voids, can be a critical design factor. This study tries to propose a better formula in calculating the through-flow velocity. Based on 19 experimental data, this study proposed a slightly better formula than the original one in terms of root-mean-square error and determination coefficient.

Key words: Nature-like fishway, rocky ramp fishway, through-flow velocity.

INTRODUCTION

A dam is a useful structure to retain water, which benefits human society in terms of agriculture. However, it also harms wildlife such as anadromous fish. Existing dams are obstacles to fish which want to spawn upstream. Thus, in order to conserve fish habitat, fish passage can be considered next to dam site. Previously, fish passage facilities have been made of hard-engineered structures; however, engineers have given more attentions to nature-like fishways recently. Two major types of nature-like fishways are pool and riffle type and rocky ramp type (Kells et al., 2000): the former is stair-step shaped while the latter has a long sloping channel with large boulders that can be used as resting areas (Kim and Kim, 2001). When focusing on rocky ramp type fish way, interstitial or through-flow velocity is a critical design factor, which is defined as the average velocity over water flow through rock voids. Abt et al. (1991) derived a formula of through-flow velocity from an experiment of coarse porous media of stone material ranging from 1.0 inch (26 mm) to 6.2 inch (157 mm) in median diameter:

$$V_t = 0.23\sqrt{gD_{10}S} \tag{1}$$

where V_t is through-flow velocity (ft/s); g is acceleration of gravity (32.2 ft/s²); D_{10} is stone diameter (inch) at which 10% of the weight is finer; S is slope expressed in decimal form.

This formula considers the relationship between velocity and slope directly from experiments without considering friction factor (Li et al., 1998). However, one former research (Stephenson, 1979) also considered the friction factor under the similar structure (square-root type formula). These two researches provided a practical procedure to calculate the flow velocity through riprap and specified that the velocity is a function of riprap properties (Pagliara and Lotti, 2009). In SI unit, Equation 2 can be expressed as:

$$V_t = 0.79\sqrt{gD_{10}S} \tag{2}$$

where V_t is through-flow velocity (m/s); g is acceleration of gravity (9.81 m/s²); D_{10} is stone diameter (m).

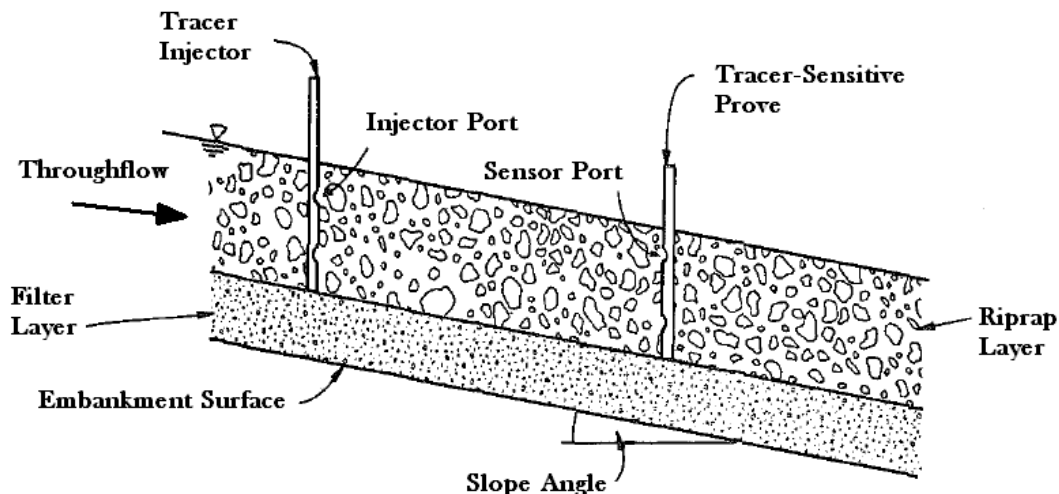---

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Figure 1. Schematic of embankment for measuring through-flow velocity.

Table 1. Experimental results for through-flow velocity.

Test Number	D_{10}		S	V_t	
	Inch	meter		fps	m/sec
1	0.60	0.015	0.01	0.10	0.030
2	0.60	0.015	0.02	0.13	0.040
3	0.60	0.015	0.10	0.24	0.073
4	1.10	0.028	0.01	0.15	0.046
5	1.10	0.028	0.02	0.23	0.070
6	1.10	0.028	0.10	0.36	0.110
7	1.10	0.028	0.10	0.37	0.113
8	2.00	0.051	0.20	0.72	0.219
9	2.00	0.051	0.20	0.97	0.296
10	3.45	0.088	0.20	1.04	0.317
11	3.45	0.088	0.20	0.86	0.262
12	3.80	0.097	0.20	1.47	0.448
13	1.03	0.026	0.10	0.46	0.140
14	1.03	0.026	0.10	0.50	0.152
15	1.03	0.026	0.10	0.54	0.165
16	2.00	0.051	0.10	0.62	0.189
17	2.00	0.051	0.10	0.66	0.201
18	1.20	0.030	0.10	0.48	0.146
19	2.38	0.060	0.10	0.66	0.201

The aforementioned formula was derived from a linear regression analysis of 19 experimental data. However, this study questions whether there is a better formula to represent the data set.

FORMULA IMPROVEMENT

Abt et al. (1991) constructed an experimental embankment as shown in Figure 1, and then obtained 19 experimental data as specified in Table 1. In the experiment, a salt tracer was utilized for measuring the through-flow velocity. Using a linear regression analysis with the 19 experimental data, Equation (1) was derived. However, they used square-root type formula for representing the data set, which has the exponent of 0.5 for D_{10} and S. But, what if the exponential value was not fixed to 0.5? Presumably, the following expression can represent the data set better than Equation (1):

$$V_t = 0.23 g^\alpha D_{10}^\beta S^\gamma \tag{3}$$

Where α, β, γ are exponential coefficients. Here, if we consider the gravity acceleration as a constant, we can obtain the following equation:

$$V_t = \omega D_{10}^\beta S^\gamma \tag{4}$$

where ω is a coefficient.

The coefficients (ω, α, β) of Equation (4) can be obtained using an optimization technique with the following objective function:

$$\text{Minimize } RMSE = \sqrt{\frac{\left(V_t^{Obs} - \omega D_{10}^\beta S^\gamma\right)^2}{n_d}} \tag{5}$$

where $RMSE$ stands for root-mean-square error; V_t^{Obs} is the observed through-flow velocity; and n_d is the number of data (=19).

RESULTS AND DISCUSSION

When Equation (5) was optimized, better coefficient values (ω = 1.0798, α = 0.5731, β = 0.4153) were obtained as follows:
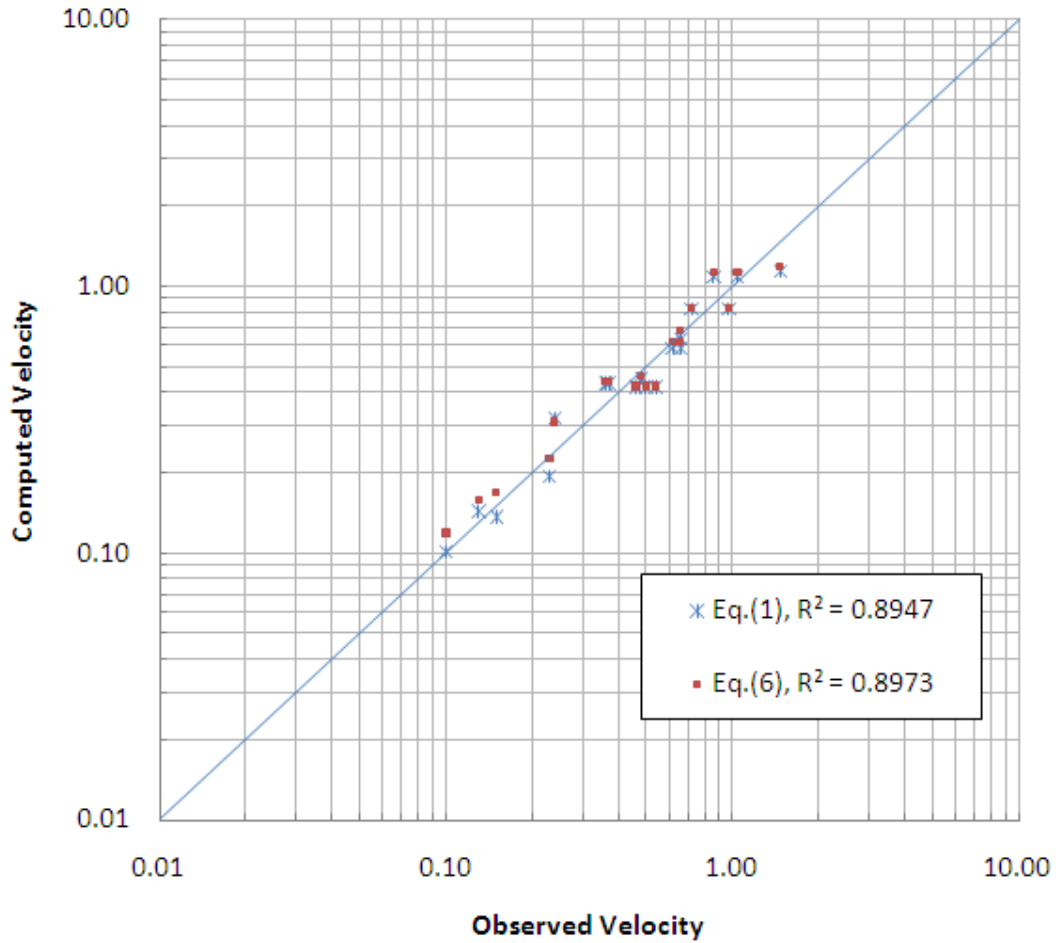
Figure 2. Comparison of Equations 1 and 6.

$$V_t = 1.0798 D_{10}^{0.5731} S^{0.4153} \tag{6}$$

When compared with the original formula, the exponent for D_{10} was changed from 0.5 into 0.5731 and that of S was changed from 0.5 into 0.4153. Equation 6 represents the data set in Table 1 slightly better than Equation 1 because the former's RMSE is 0.1100 while the latter's RMSE is 0.1131. Also, the former's determination coefficient (R^2) is 0.8973 while the latter's one is 0.8947 (the original paper claimed R^2 was 0.92, but it was corrected as 0.8947 in this study).

Although the difference in two equations for calculating the open-channel flow velocity is very little in terms of RMSE and determination coefficient, this study has a value by giving the message that we do not have to constrain the slope to be in the format of square-root. Similar phenomenon can be already found in piped flow velocity calculation. Although the difference in two popular equations (Darcy-Weisbach equation as specified in Equation 7 and Hazen-Williams equation as specified in Equation 8) for calculating the pipe flow

velocity is very little, both are frequently used Geem et al., 2011; Geem, 2006). Furthermore, Hazen-Williams equation, which has the slope exponent value of 0.54 instead of square-root format, is more popular for the water pipe design:

$$V_p = \sqrt{\frac{2}{f}} \sqrt{gDS_e} \tag{7}$$

$$V_p = k C_{HW} R^{0.63} S_e^{0.54} \tag{8}$$

where V_p is piped flow velocity; f is Darcy-Weisbach friction factor; D is pipe diameter; S_e is energy slope; k is conversion factor for the unit system; C_{HW} is Hazen-Williams roughness coefficient; and R is hydraulic radius.

Figure 2 shows the comparison of the results from Equations 1 and 6. As shown in the figure, two equations predicted the observed velocities quite well; however,

Equation 6 slightly outperformed Equation (1) in terms of R^2 and RMSE as mentioned earlier. To see if better coefficient values were obtained, Equation (4) was further modified as follows:

$$\ln(V_t) = \ln \omega + \beta \ln(D_{10}) + \gamma \ln(S) \tag{9}$$

And, the objective function was also modified as follows:

$$\text{Minimize } RMSE = \sqrt{\frac{\left(\ln(V_t^{Obs}) - [\ln \omega + \beta \ln(D_{10}) + \gamma \ln(S)]\right)^2}{n_d}} \tag{10}$$

However, the coefficient values obtained by optimizing Equation 10 were identical to those by optimizing Equation 5.

Conclusions

This study proposed a better structure of through-flow velocity formula used for nature-like fishway design. The research focus was how we could further improve the existing through-flow velocity formula by more reducing the error between observed and model-calculated data. In that sense, this study did not stick to the existing square-root type formula.

Thus, we could find better values for two exponents (one for stone diameter, and the other for river slope) in the previous square-root type formula. The optimized exponent values for the new formula based on original experimental data further minimized the error between observed and computed velocities with respect to RMSE while enhancing the relationship between the two with respect to R^2. This new concept of freedom in the function structure is a contribution of this study.

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