Head Loss Equation of Flow Through Rockfill

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1. Introduction

Rock has been advantageously employed in hydraulic structures such as flowthrough dams, cofferdams, gabion weirs and drain works. To predict flow transmissibility of the structures, an accurate evaluation of hydraulics of flow through rockfill is required. Analysis of flow through rockfill is complicated because of non-linear relationship between a discharge velocity through the rockfill and a hydraulic gradient applied. In this study, a head loss equation of flow that defines the non-linear relationship mentioned above is investigated based on laboratory tests and a numerical parameter estimation procedure. Firstly a Forchheimer-type equation of head loss is proposed, then the parameter estimation procedure combining a finite element method with a genetic algorithm (FEM-GA) is developed to determine non-linear coefficients included in the head loss equation of flow.

2. Head loss equation of flow through rockfill

One-dimensional permeability tests of rock particle column were conducted. Being washed and air-dried, the river gravel was sieved into six classes of size, D1 to D6. Classes of rock particle, and their representative diameter, rock particle shape and physical properties of the rock particles are given in **Table 1**. The rock particles were classified according to the Zingg diagram into four shapes. Their frequencies are given in the rows (4)-(7) of **Table 1**. The mean shape coefficient of rock particles, *r*, in the row (8) is calculated as a mean of r_e weighted by the frequencies measured in the rows (4)-(7), in which r_e is the shape coefficient for each shape of rock particles measured by Sabin and Hansen (1994).

Typical results of the one-dimensional permeability tests of rockfill are shown in **Figure 1**. It is shown that the discharge velocity of flow through the rockfill specimen, *V*, has a non-linear relationship with the hydraulic gradient applied to it, *i*. This relationships between *i* and *V* can be well given by

$$i = \frac{A_0 \cdot \nu}{g} \cdot V + \frac{B_0}{g} \cdot V^2 \qquad (1)$$

in which A_0 and B_0 are the coefficients depending only on the void structures of rockfill, ν is a kinematic viscosity of water, and *g* is an acceleration of gravity. Effects of the void structures on the head loss property of flow should be evaluated by taking the size and shape of rock particles as well as the size and distribution of voids within the rockfill into account. Martins (1990) showed that all the effects mentioned above could be well explained by a hydraulic mean radius of voids, *m*, which is defined as

$$m = \frac{e \cdot d}{6 r_e} \qquad (2)$$

where *e* is a void ratio of rockfill.

3. Relationship of A_0 and B_0 with *m*

The FEM-GA can be applied to observations of flow

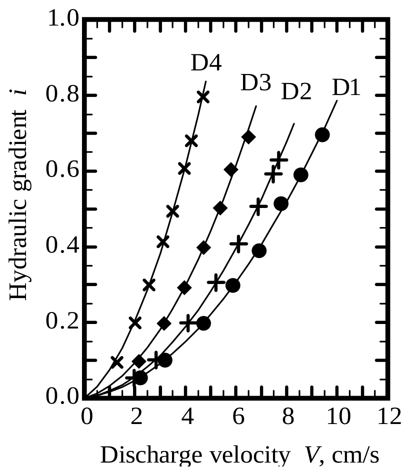

Figure 1 Typical results of one-dimensional permeability tests of river gravel 5 to 25 mm in diameter.

Table 1 Size, shape and physical properties of the rock particles used in the one-dimensional permeability tests.

Class of rock particle (1)	Particle size, mm (2)	Arithmetic mean of particle size *d*, mm (3)	Blades (4)	Disks (5)	Spheroids (6)	Rods (7)	Mean shape coefficient *r* (8)	Specific gravity of dried particle G (9)	Water absorption of particle, % (10)
D1	20-25	22.5	0.32	0.22	0.14	0.32	1.9314	2.563	1.4
D2	15-20	17.5	0.22	0.18	0.26	0.34	1.8600	2.550	1.5
D3	10-15	12.5	0.22	0.24	0.20	0.34	1.8774	2.557	1.4
D4	5-10	7.5	0.32	0.16	0.06	0.46	1.8944	2.575	1.6
D6	25-50	37.5	0.17	.0.40	0.16	0.27	1.9051	2.550	1.2
D5	50-75	62.5	0.18	0.38	0.14	0.30	1.9008	2.601	0.9

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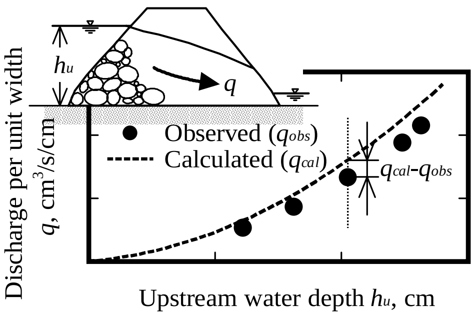

Figure 2 Difference between calculation and observation to be minimized.

through prototype rockfill embankment to estimate the non-linear coefficients A_0 and B_0 defined in Equation (1). Most optimum values of the coefficients are determined so that a summation of deviations between observation and calculation of stage-discharge rating curve, h_u-q, as shown in **Figure 2** becomes minimum by genetic calculations. h_u is a upstream water depth of reservoir and q is a flow discharge per unit width of rockfill.

Using the river gravel D1 to D6, the rockfill embankments were constructed in the laboratory water flumes 20 cm wide as well as 50 cm wide. Mass and volume of the embankment were measured to calculate e and m. Fifteen and twelve laboratory embankments with the different size of rock particle, downstream slope and top width of the embankment were tested in the small and large water flumes, respectively. h_u was raised in 4 to 5 steps, and q of a steady state flow through the embankment was measured in each step of h_u,. The FEM-GA was applied to determine A_0 and B_0 that explained optimally the h_u-q curve observed. Crossover and mutation rates were 0.25 and 0.01, respectively, in the FEM-GA. **Figure 3** shows the plots of A_0 and B_0 with the measured values of m. Unique relationships of A_0 and B_0 with m found in **Figure 3** shows a practical effectiveness of the head loss equation of flow through rockfill proposed by Equation (1). Accuracy of the head loss equation of flow may be also examined by good comparisons of the discharge flow **in Figure 4** and of the hydraulics within the embankment in **Figure 5** between the laboratory observations and the FEM calculations using the estimated non-linear coefficients.

4. Conclusions

The head loss equation of flow through rockfill was successfully determined The non-linear coefficients included in the head loss equation of flow were effectively correlated to the hydraulic mean radius of voids. The FEM-GA analysis of the laboratory water flume tests showed that the head loss equation of flow developed in the study was valid for the wide range of rock particle size, 5 to 75 mm in diameter. Rockfill structures are economical ones from the geotechnical point of view, and are friendly to our environment. Understanding the rockfill hydraulics may give us a good design procedure of the rockfill structures, and as well may show us a new idea of mitigation works for our environment.

References

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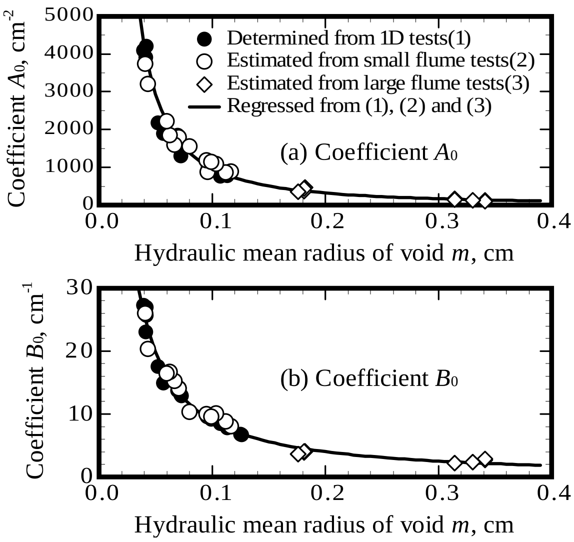

Figure 3 Unique relationships of A_0 and B_0 with m.

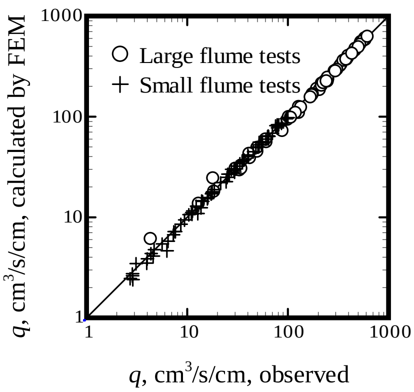

Figure 4 Comparison of flow discharge through laboratory embankments between observation and FEM calculation.

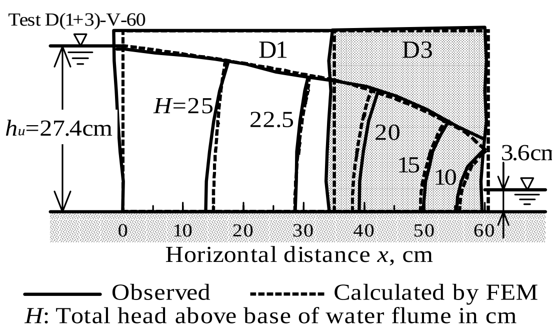

Figure 5 Comparison of flow hydraulics measured within the laboratory embankment with the FEM calculation using the estimated non-linear coefficients.