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The authors would like to express their appreciation for the discusser for his valuable comments and advice on rubble mound weir from various engineering points of view. The authors were able to learn that such various types of rubble mound structures are in practical use for a wide spectrum of engineering purposes in Australia, while the authors' interest was limited to a problem of rubble mound weirs being lower than rockfill dams. On the other hand, the authors were encouraged through the discussion to learn that the authors' study may provide fundamental information on rubble mound structures and that the study could be further extended in different directions.

The authors' understanding is that the discussion consists of two parts. The first is the problem of rubble mound weirs with different types of internal and external structures such as the in-built spillway dam and the stepped weir. The second is with respect to a hydrodynamics in the case of rubble mound weir with overflow.

Rubble mound weirs with different types of internal and external structures

From an engineering point of view, it is a useful method for controlling through-flow discharge to partially install an in-built spillway or less permeable materials in a rubble mound structure (e.g. Parkin, Trollope and Lawson 1966, Curtis, and Lawson 1967). One of the problems with this type of structure, however, is the supposed difficulty in maintenance and repair work. The rubble mound weir must be designed under a concept that the structure could fail with severe flood flows. The basic idea is that the structure must be repaired and overhauled with a certain frequency. This is completely different from the design concept of conventional solid structures of concrete and steel. In the old ages, local inhabitants used to cooperate with each other to repair the weir after heavy stormwater. The repair work had a function to tighten the local community (Michioku 2003). In this sense, inhomogeneous structures are not suitable to the rubble mound weir, since complicated and special techniques are needed to repair the failed structure. An additional problem from an analytical point of view is that the one-dimensional flow analysis is no more applicable in the case of inhomogeneous rubble mound weir. A two or three dimensional analysis for the porous media flow is necessary, which is itself a fascinating scientific topic and worthwhile to be investigated but is beyond the authors' scope.

As pointed out in the discussion, the authors did not mention a rubble mound weir with complicated external profile such as stepped weir. The authors partially agreed with the discusser at this point, because the rubble mound weir, strictly speaking, should have slopes at both the up- and downstream ends for stabilizing the structure. The authors, however, consider that their analysis for the rectangular weir is still useful because weirs used for irrigation are usually lower compared to a rockfill dam and thus the depth-to-length ratio is quite small. This means that even the trapezoidal weir can be well approximated by an equivalent rectangular weir and a one-dimensional flow analysis is expected to give a good solution for the flow through rubble mound weir.

Interactions between seepage and overflow

The analysis and experiment in this paper was limited to a case in which the water surface is submerged in the rubble mound (see (c) Figure 1). The authors agree with the discusser on the point that it is necessary to further investigate the situation in which flow runs over the weir as shown in Figure 1(a), although little literature is found in this field. Michioku and Maeno (2004) and Maeno and Michioku (2004) has already extended the study to this situation, carried out an experiment as shown in Photo 1, and developed a one dimensional model for analyzing flow discharge and water surface profile. Although the result was already contained in the conference proceedings, the authors are not yet ready to submit a paper to a journal.. Here, the concept of the model and a part of the results are shown in brief.

Interaction between the seepage and overflow is exactly a key in the flow analysis. As illustrated in Figure 2, the flow is assumed to be a two-layer structure consisting of a free surface flow over the weir and a turbulent seepage flow in the weir. One-dimensional continuity equations were formulated as follows.

$$\frac{d}{dx}\left(U_{\mathrm{U}}h\right)=q_{\mathrm{i}}=-\frac{d}{dx}\left(U_{\mathrm{L}}nW\right)=-\frac{d}{dx}\left(U_{\mathrm{S}}W\right) \tag{1}$$

U_{U} is the velocity in the upper layer, and U_{L} is the seepage fluid velocity in the weir. U_{L} is related to apparent velocity U_{S} as $U_{\mathrm{S}}=nU_{\mathrm{L}}$ in terms of porosity n. q_{i} is the exchange rate or entrainment velocity between the upper and lower layers.

Momentum balances in the two layers are written as follows:

$$\underbrace{\frac{d}{dx}\left(\frac{U_{\mathrm{U}}^2}{2g}\right)}_{\text{(I)}}+\underbrace{\frac{dh}{dx}}_{\text{(II)}}\underbrace{-i}_{\text{(III)}}+\underbrace{\frac{\tau_{\mathrm{w}}P}{\rho gA}}_{\text{(IV)}}+\underbrace{E\frac{q_{\mathrm{i}}}{gh}(U_{\mathrm{U}}-U_{\mathrm{S}})}_{\text{(V)}}=0 \tag{2}$$

$$\underbrace{\frac{d}{dx}\left(\frac{U_{\mathrm{L}}^2}{2g}\right)}_{\text{(I)}}+\underbrace{\frac{dh}{dx}}_{\text{(II)}}\underbrace{-i}_{\text{(III)}}\underbrace{-E\frac{q_{\mathrm{i}}}{gW}(U_{\mathrm{U}}-U_{\mathrm{S}})}_{\text{(IV)}}+\underbrace{C_1U_S+C_2U_S^2}_{\text{(V)}}=0 \tag{3}$$

In the equations, τ_{W} is wall friction, and (A, P) are the cross section area and wetted perimeter in the upper layer. Refer to Figure 2 for the other variables. E is the entrainment coefficient in respect to mass and momentum exchange between the two-layer's interface. Drag force in the rubble mound or the term (V) in Eq.(3) is formulated by using the flow resistance law as mentioned in the authors' paper, where the coefficients C_1 and C_2 are given as functions of a porous body's parameters such as porosity, grain diameter, etc.

A solution for a water surface profile is obtained by integrating the set of equations under a given discharge. As recognized in the Photo 1, a control section appears at the downstream end of the weir. Then, a singular point condition is applied in order to obtain a solution for discharge. An example of the solutions for normalized discharge F_0 is plotted as a function of dimensionless weir height w, which is compared with the laboratory data in Figure 3. Good agreement between the theory and experiment is confirmed.

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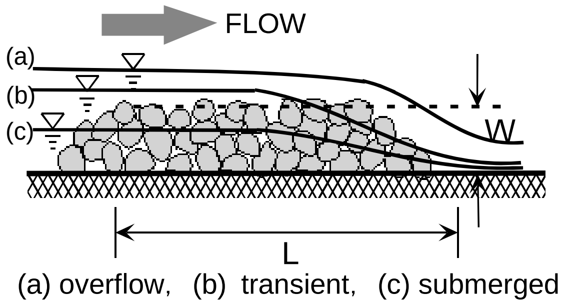

Figure 1 Flow around a rubble mound weir

Photo 1 A side view of the laboratory experiment

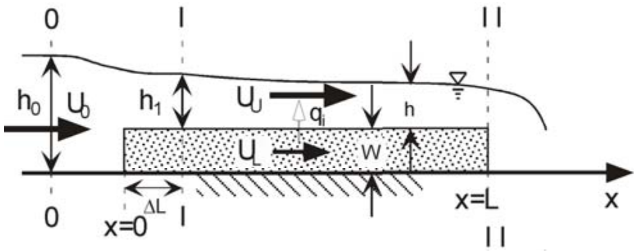

Figure 2 Flow system

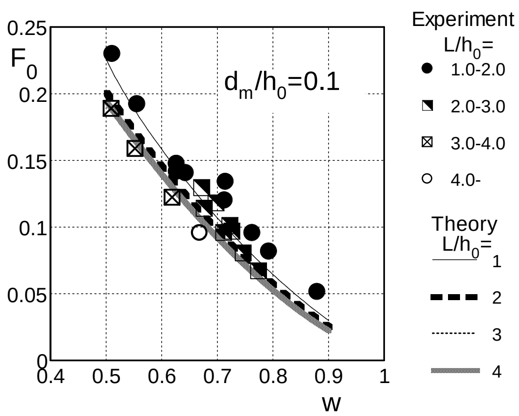

Figure 3 Dimensionless discharge F_0 plotted against dimensionless weir height $w=W/h_0$