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EXPERIMENTAL STUDY ON HYDRAULIC CHARACTERISTICS OF BOTTOM INTAKE WITH GRANULAR POROUS MEDIA

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Bottom rack intake is one of the most appropriate hydraulic structures for diverting water in steep rivers. The problems of corrosion and deformity of the bottom racks in the long term inspires a new system of bottom intake in which a filled trench of porous media replaces the bottom racks. In this article, the hydraulic characteristics of this intake are investigated in an experimental model designed in a two-storey channel. The lower channel is used to convey diverted water through the porous media, and the upper one is used to carry the remaining flow to downstream. Measurements of the diverted discharge were performed for different rates of flow, grain size distributions, and surface slopes of intake. Results show that the diverted discharge increases whenever the surface slope of bottom intake decreases, the inflow discharge increases and or coarse grains are used in the intake. The empirical equation for estimating the discharge coefficient (C_d) of bottom intake shows that the C_d of porous media intake is about 0.1. To calculate the diverted discharge of intake, an empirical-theoretical relation has been proposed. The theoretical predictions in comparison with the experimental results have shown good consistency.

KEY WORDS: *bottom intake, porous media, discharge coefficient, water surface profile*

1. INTRODUCTION

Water diversion by bottom intake is one of the most common methods of water conveyance from a river to side channels. Trash rack is one kind of bottom intake that is often adopted in relatively small mountain rivers, where steep slopes, irregular bed configuration, instant transport, and rapid floods prevent the use of gated dams (Bouvard, 1992). Bottom racks are also used in the construction of debris flow breakers (Mizuyama and Mizuno, 1994). In some cases, prismatic channels upgrading downstream and with a perforated bottom are used as energy dissipaters (Viparelli, 1963). Generally, diversion structures are designed to divert the maximum discharge of water. Moreover, in critical conditions, where the entire bed loads pass over the stream bed intake, the longitudinal bars are used for bottom intakes to reduce clogging effects (Righetti and Lanzoni, 2008). However, corrosion and deformity of the bars, clogging, and maintenance are the common problems of bottom racks, which make them unusable in the long term.

To solve these problems, a new system of bottom intake with porous media is introduced. It is obvious that diversion of a specified amount of discharge through the porous media in comparison to the bottom racks requires a much larger structure. However, it is believed that this kind of water intake does not have any inconsistency with the river morphology because the granular materials that are used in the intake are similar to bed materials.

The first hydraulic description of bottom intakes was provided by Orth et al. (1954), investigating flows on a 20% sloping channel, and by Drobir (1981), with prototype structures leading to optimum rack slopes of 20% to 30%.

NOMENCLATURE

A	surface area of porous media intake (m^2)	V	theoretical flow velocity in porous media (m/s)
B	width of porous media intake (m)	V_p	actual velocity in the porous media (m/s)
C_d	discharge coefficient (dimensionless)	V_1	flow velocity in upstream channel (m/s)
d_{50}	mean grain size of porous media (m)	V_2	flow velocity in diversion channel (m/s)
Fr_1	Froude number of upstream flow (dimensionless)	y_{c1}	critical depth at the beginning of the intake
g	gravitational acceleration (m/s^2)	y_{c2}	critical depth at the end of the intake
h_f	energy loss in porous media (m)	y_0	normal depth of the upstream channel
L	length of porous media intake (m)	y_{1c}	flow depth at the beginning of the intake
n	porosity of specimen (dimensionless)	y_{2c}	flow depth at the end of the intake
P_n	mean diameter of grain sizes for n = 1–4 (m)	y_1	water depth in upstream (m)
Q	inflow discharge to the porous media (m^3/s)	y_2	water depth in diversion channel (m)
Q_d	diverted discharge of porous media intake (m^3/s)	Z_1	elevation of upstream channel (m)
Q_r	remain discharge on upper channel of porous media intake (m^3/s)	Z_2	elevation of downstream channel (m)
Q_t	inflow discharge (m^3/s)		
S_p	surface slope of porous media intake (dimensionless)		

Greek Symbols

γ	slope of the bottom intake (dimensionless)
ρ	water density
ψ	relative diverted discharge (dimensionless)

In bottom intakes, introducing a relationship to estimate the diverted flow discharge still needs more research. Generally, the rate of change of the diverted discharge per unit width is given by the relationship (Righetti and Lanzoni, 2008)

$$\frac{dq}{dx} = C_q \omega \sqrt{2gY} \tag{1}$$

where dq is the discharge per unit width diverted along a piece of grid of length dx; C_q is the discharge coefficient; ω is the void ratio, that is, the ratio of the opening area to the total area; and Y is the suitable value of the hydraulic head. To estimate the flow discharge through a bottom rack, different relationships are proposed in the literature that confirm that the values assumed by C_q are strictly linked to the definition of the hydraulic head. Different approaches have been proposed in the literature to evaluate C_q and Y. Studies show that different parameters are used to define the relevant hydraulic head Y in Eq. (1), including specific flow head of the flow approaching the rack, local flow depth, and local value of the mean flow depth along the channel. Accordingly, there is no univocal definition of the relevant hydraulic head to be introduced in Eq. (1) (Righetti and Lanzoni, 2008). Theoretical analyses assume that the flow field above the rack can be treated as one-dimensional (Venkataraman et al., 1979), and another assumption usually employed is that energy dissipation along the rack is either negligibly small (Bouvard, 1953; Mostkow, 1957) or balances the bottom slope (Noseda, 1955). The measurements of free surface velocities carried out by Brunella et al. (2003) confirm that dissipative effects are negligible, except toward the end of the rack (Righetti and Lanzoni, 2008). Based on the experimental studies, Subramanya and Shukla (1988) and Subramanya (1990, 1994) classified the flows over horizontal and sloping racks of rounded bars, summarized in Table 1.

Despite differences between bottom intakes with trash racks and the new system with porous media, there are some hydraulic similarities. For instance, as the main flows in both intakes are spatially varied flows with decreasing discharge, similar surface profiles can be predicted in both systems. However, the diverted discharge of bottom rack intake is in orifice form, while in porous media intake, it varies based on the flow regime. When the granular material are finer, both the hydraulic and friction resistances of flow increase, which consequently leads to

TABLE 1: Types of water surface profiles on the bottom rack intake (Subramanya and Shukla, 1988)

Upstream flow	Flow on bottom intake	Downstream flow	Profile type
Hydraulic jump	Supercritical	Subcritical	A1
Subcritical	Hydraulic jump	Subcritical	A2
Subcritical	Subcritical	Subcritical	A3
Hydraulic jump	Supercritical	Supercritical	B1
Subcritical	Hydraulic jump	Supercritical	B2

a decrease of flow velocity and an increase of water surface profile (Leps, 1973).

In the seepage flow hydraulic of the porous media, the flow velocity is defined in two methods. The first relationship is

$$V = \frac{Q}{A} \tag{2}$$

where V is the apparent velocity in porous media; Q is the inflow discharge to the porous media; and A is the surface area of bottom intake toward the inflow discharge. The other relationship is (Li et al., 1998)

$$V_p = \frac{V}{n} = \frac{Q}{nA} \tag{3}$$

where V_p is the actual velocity in the porous media and n is the porosity of the porous media.

This article reports on the flow simulation of a bottom intake with a filled trench of porous media in an experimental model under different hydraulic conditions of pure water flow. During the experiments, the hydraulic conductivity of the porous media is investigated. The experiments involve a number of variables, namely, discharge, surface slope of the bottom intake, and type of granular material. The granular material used in the new system of water intake can be found easily in the field. Maintenance and higher compatibility with the river morphology in the long term are considered as major advantages. Recognition of the effective parameters on applicability of porous media intake and providing conditions to improve the efficiency of diverted discharge of this system are the main aims of this research.

2. EXPERIMENTAL SETUP

The experimental setup used for simulating the flow diversion through porous media is shown in Fig. 1. The setup consisted of a flume with 10 m in length, 0.3 m in width, and 0.5 m in depth (Fig. 2), in which a galvanized rectangular box of 20 cm length, 30 cm width, and 10 cm height was filled with coarse granular material. The box, which is shown in Fig. 1, was set at a distance of 5.0 m from the upstream entrance of the flume.

At the immediate downstream of the box, the flume consisted of a two-storey channel. The role of the lower

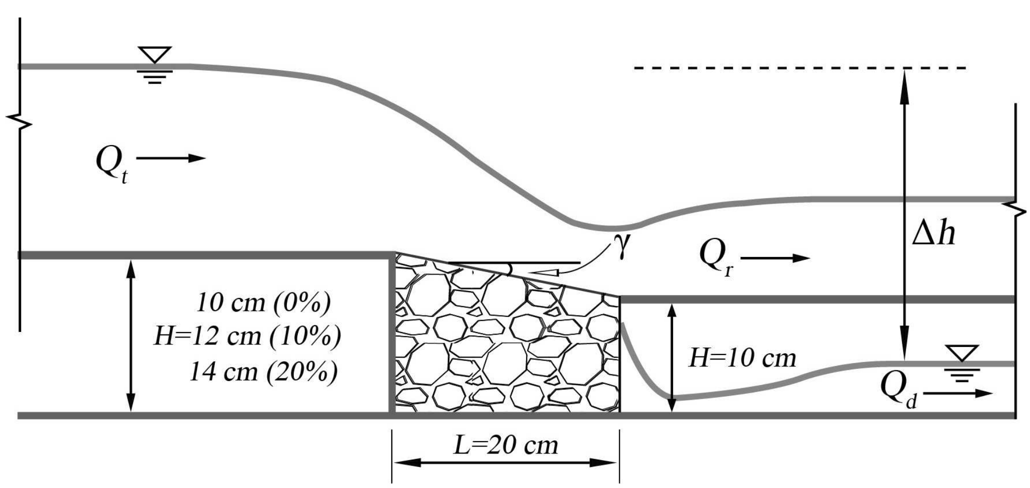

FIG. 1: Sketch of water intake frame as trench of porous media with different heights.

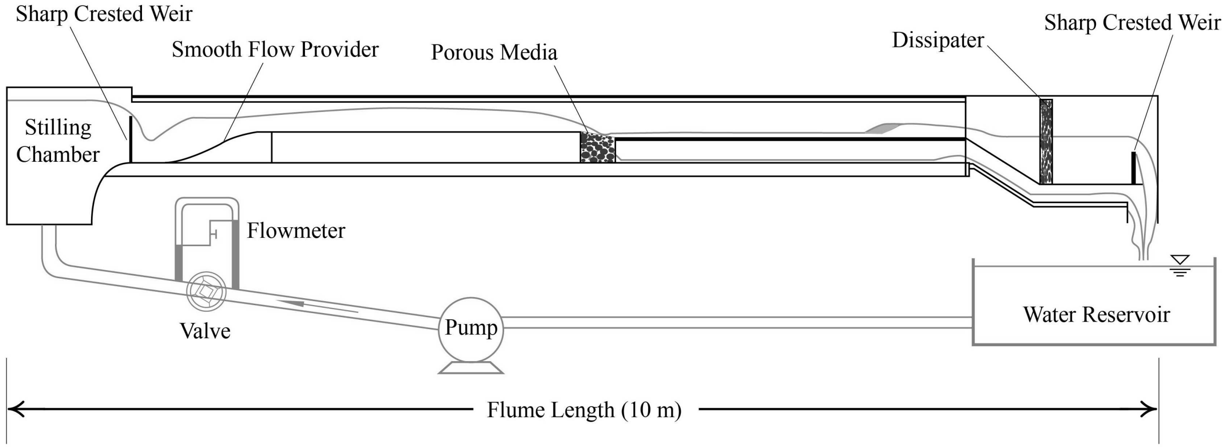

FIG. 2: Longitudinal section of the experimental setup.

channel was to convey the diverted discharge Q_d, and the role of the upper one was to carry the remaining discharge Q_r.

A rectangular weir was set at the end of the upper flume to measure Q_r. The diverted and remaining discharges were collected in a tank located below the flume and pumped to the stilling chamber, which was located at the upstream of the inlet section. The total discharge Q_t was measured by an orifice meter located immediately downstream of the pump and double checked by a rectangular weir at the end of the stilling chamber. Then the diverted flow was calculated based on the fact that the diverted and remained discharges were equal to the total discharge. The maximum surface slope of the box is usually restricted to 20%, as stated in the literature (e.g., Brunella et al., 2003).

In the present work, the slopes of 0%, 10%, and 20% were used for the upper surface slope of the specimen (Fig. 1). To prevent any movement of the material downstream, the vertical face of the box of granular material was covered with a number of horizontal bars, and also, a miniature wire net was set over the upper face.

Longitudinal slope of the flume was set as 0.005 in all runs. In each run, the diverted discharge and flow depths of the upper and lower flumes (hydraulic gradient) were measured.

Efficiency of the porous media intake was examined by four different types of gravel with average diameter (d_{50}) 8.5, 11.5, 14.5, and 17.5 mm and symbol P1, P2, P3, and P4, respectively (Fig. 3). Other variables are three slopes of intake and eight different discharges between 3.4 L/s and 23.8 L/s.

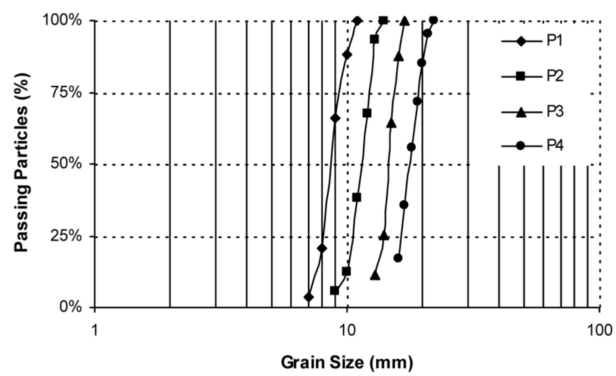

FIG. 3: Grain size distribution of porous media.

3. EXPERIMENTAL RESULTS

The results of relative diverted discharge ψ, defined by Eq. (4), are shown in Fig. 4:

$$\psi = \frac{Q_d}{Q_t} \times 100 \tag{4}$$

where Q_d is diverted discharge of porous media and Q_t is total discharge.

According to Fig. 4, it is obvious that in all cases, the discharge increment leads to the decrement of ψ. It is believed that the water conveyance through porous media is related to a power of head loss, Δh. However, by increasing Δh, the amount of diverted discharge will not increase linearly at constant values of ψ. The variation of relative diverted discharge is almost between 100% and 29%, which occur in lower and higher discharges, respectively. For coarse grain sizes, as the void spaces of spec-

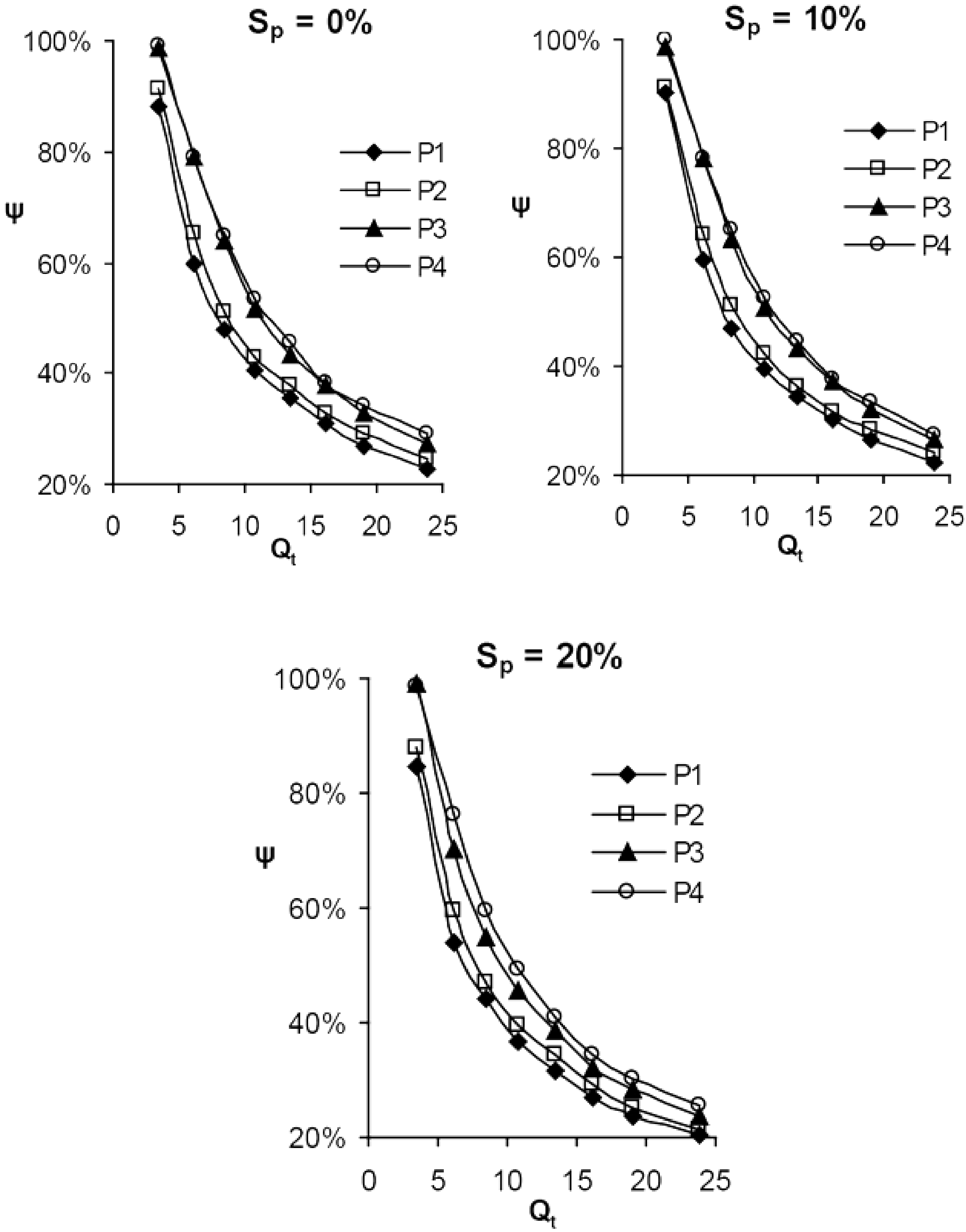

FIG. 4: Effect of grain size distribution on ψ variations in different surface slopes.

imens are larger, much water is conveyed to the diverted channel, and consequently, ψ will increase. The ψ differences in different surface slopes (Table 2) show that the efficiency of bottom intake in water diversion for S_p = 20% is less than two other slopes. Furthermore, the results of zero surface slope of the intake, that is, S_p = 0%, show better performance than S_p = 10%. These results are in agreement with the observations of Righetti and Lanzoni (2008). They have stated that as the surface slope of bottom intake increases, the entrance angle of streamline to intake will decrease, and thereby the vertical vector of entrance velocity in comparison to the horizontal vector will decrease. Because of the horizontal velocity vector increase, most of the flow passes over the intake, and a small percentage of it will divert to the intake channel. In Table 2, the minimum and maximum values of ψ are given for different size distributions and surface slopes of porous media.

3.1 Water Surface Profile

The water surface profiles on the bottom intake with porous media agree well with Subramanya and Shukla's (1988) research on bottom rack intakes. However, in the present study, most of the profiles are type B1. The hydraulic features and typical water surface profiles observed in experiments are shown in Table 3 and Fig. 5, respectively.

The mentioned parameters in Table 3 and Fig. 5 are defined as follows: y_0 is the normal depth of the upstream channel; y_{1c} is the flow depth at the beginning of the intake; y_{c1} is the critical depth at the beginning of the intake; y_{2c} is the flow depth at the end of the intake; and y_{c2} is the critical depth at the end of the intake.

Figure 6 shows the water surface profiles in different discharges for grain type P3 and surface slope $S_p = 10\%$. It is observed that the water surface slope of the lower discharges on bottom intake is greater than the slope of higher discharges. This is likely because of low flow velocity in low discharges, which leads to more water diversion of intake, and accordingly, the water depth on the end point of intake is lower than the first point.

TABLE 2: Variation of ψ (%) for different grain types and surface slopes

	S_p		
Grain type	**0%**	**10%**	**20%**
P1	22.9–88	22.4–86.5	20.6–84.5
P2	24.6–91.2	24.1–89	21.2–88
P3	27.4–98.5	26.3–98.5	23.5–99
P4	29.1–99	27.4–100	25.8–100

Comparing water surface profiles in Fig. 7 for two grain types P1 and P4 with Q_t = 6.2 L/s and $S_p = 10\%$ shows that the flow depth on the intake with coarser grain size is lower, which indicates that in this situation, much water diverts to the diversion channel. In Fig. 8, it is seen that in lower surface slopes of intake, the flow velocity is lower, and thus more water is conveyed to diverted channels and water surface slopes on the bottom intake are lower.

Moreover, in a lower surface slope, most of the inflow discharge diverts to the diverted channel from the beginning point of the intake. According to Righetti and Lanzoni (2008), in water intake with lower surface slope, much water is diverted to the diverted channel because the vertical component of the velocities is higher than the flow above the intake and tends to have a magnitude comparable with the horizontal component. The vertical component decreases moving downstream along the intake, thus implying that the diverted discharge tends to decrease. Indeed, the magnitude of the downward rotation experienced by the velocity vector near the bottom decreases progressively as one moves toward the end of the intake and, for a given value of the approaching flow depth, as the Froude number increases. Moreover, localized end effects induced by the curvature of the streamline detaching from the upstream edge of the intake and by the rear stagnation point could lead to a reduction of the diverted discharge with respect to theoretical predictions. Experimental results show that as the surface slope of bottom intake increases, the inflow velocity to intake increases too.

3.2 Diverted Discharge of Bottom Intake with Porous Media

According to Fig. 9, the simplified specific energy equation (Bernoulli) for incompressible nonviscous steady flow along the bottom intake is as follows:

$$y_1 + z_1 + \frac{V_1^2}{2g} = y_2 + z_2 + \frac{V_2^2}{2g} + h_f \tag{5}$$

where h_f is the total head loss between upstream flow and bottom intake. Experimental results show that $V_1^2/2g$ is ignorable in comparison with $V_2^2/2g$, and the velocity equation can be written as

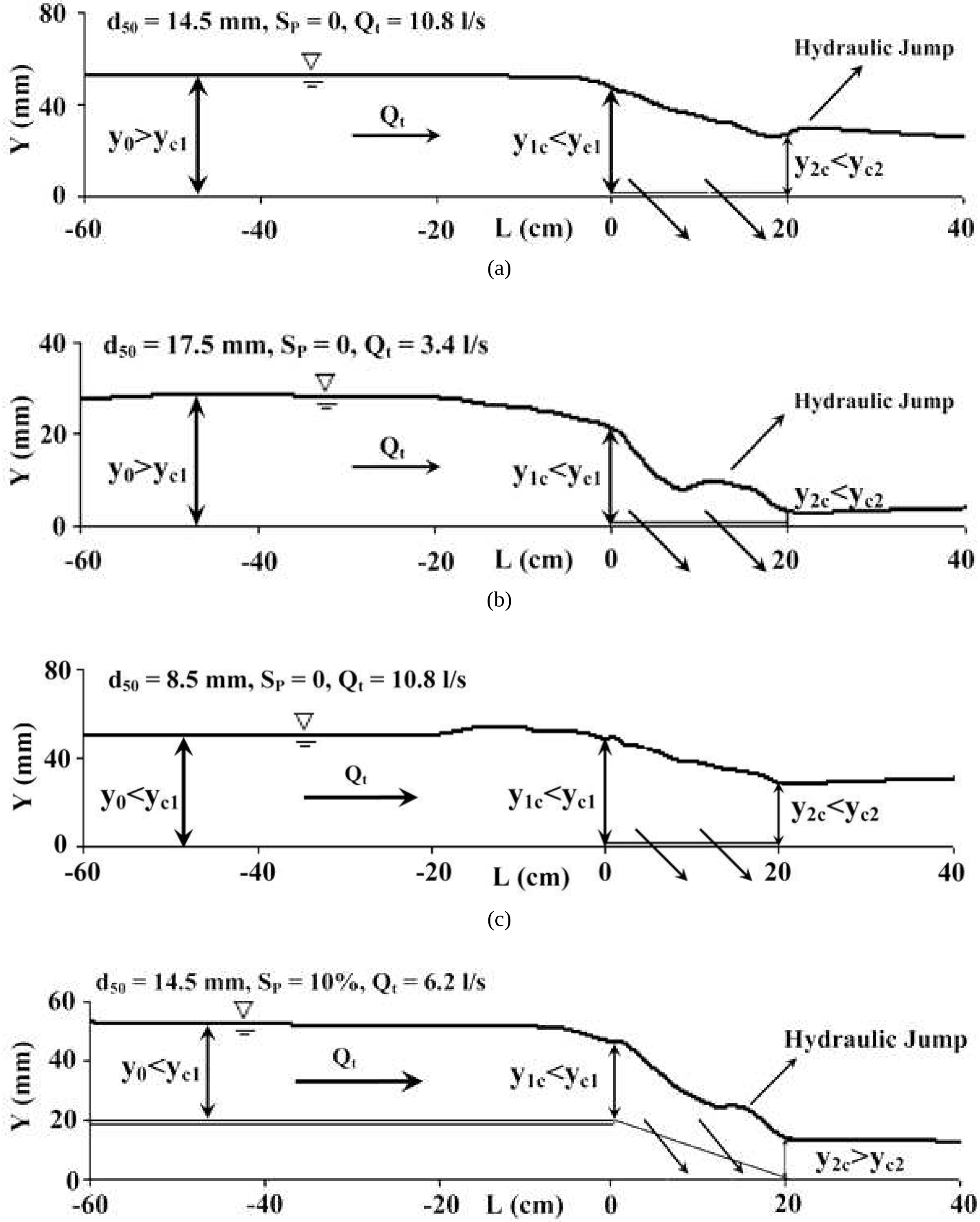

FIG. 5: Different types of water surface profiles on bottom intake with porous media.

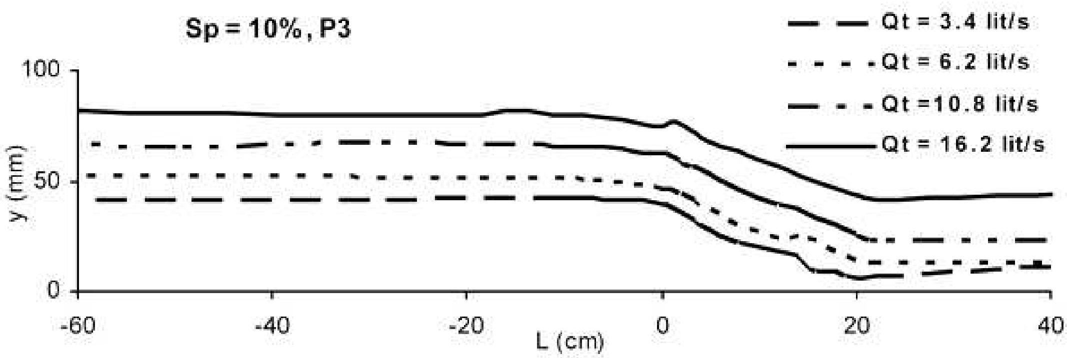

FIG. 6: Water surface profiles in different discharges (grain type P3, S_p = 10%).

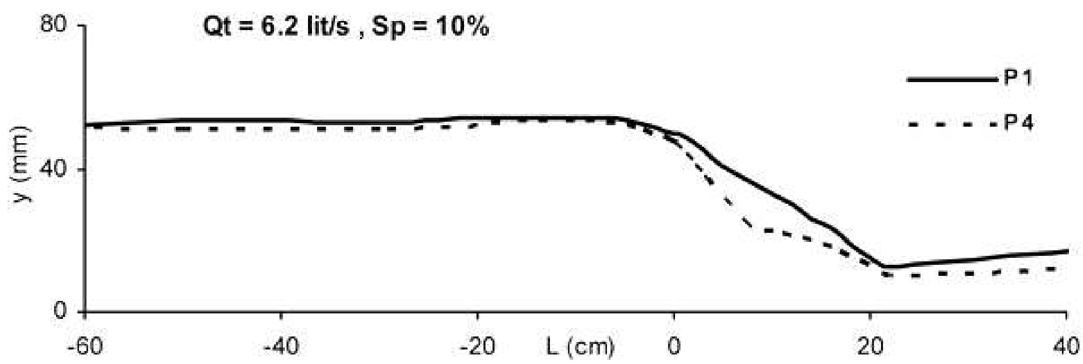

FIG. 7: Water surface profiles for grain types P1 and P4 ($Q_t = 6.2$ L/s, S_p = 10%.)

$$V_2 = \sqrt{2g\,(y_1 - y_2)\left(1 + \frac{z_1 - h_f}{y_1 - y_2}\right)} \qquad (6)$$

In this equation, h_f and z_1 are near to each other, and thus $(z_1 - h_f/y_1 - y_2)$ can be omitted. It seems that by passing flow through the porous media and the head loss, the outflow velocity of porous media is less than the inflow. However, because of the height differences between upstream and diverted channel beds and the force gravity, the head loss effect on outflow velocity is negligible.

The resulting error of this simplification will be considered in the discharge coefficient. Assuming that the outflow and inside flow velocity of intake are the same, the mean flow velocity can be obtained as follows:

$$V = \sqrt{2g\,(y_1 - y_2)} \qquad (7)$$

Considering the continuity equation and Eq. (3), the diverted discharge of bottom intake with porous media, per unit width and unit length, is as follows:

TABLE 3: The hydraulic results of the water surface profiles

y_{1c} (mm)	y_{c1} (mm)	y_{2c} (mm)	y_{c2} (mm)	Fr_1 Upstream	Upstream flow	Flow kind on intake	Downstream flow	Profile type
47.5	50.94	25	31.41	0.94	Subcritical	Supercritical	Hydraulic jump	A1
21.5	23.57	5		0.75	Subcritical	Hydraulic jump	Subcritical	A2
48.5	50.94	29	36	1.08	Supercritical	Supercritical	Hydraulic jump	B1
26.5	35.18	14	12.86	1.11	Supercritical	Hydraulic jump	Subcritical	B2

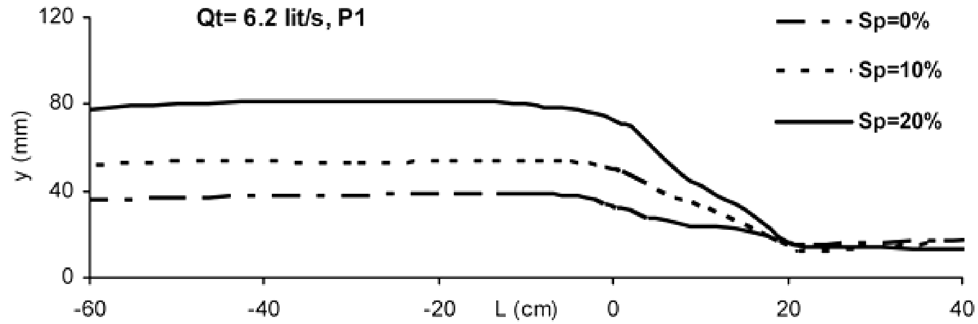

FIG. 8: Water surface profiles in different slops of intake (Q_t = 6.2 L/s and grain type P1).

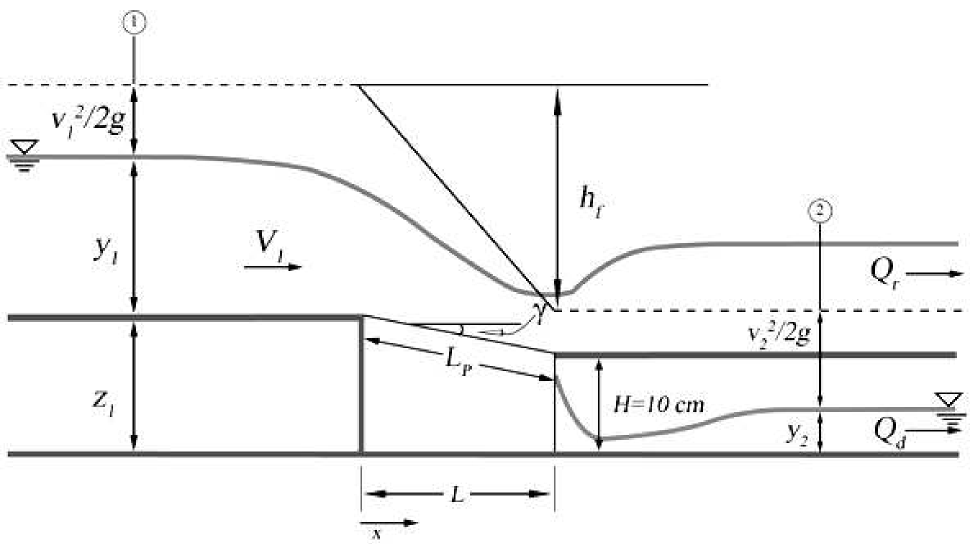

FIG. 9: Hydraulic characteristics of the flow in the bottom intake with porous media.

$$\frac{dq}{dx} = C_d n V \tag{8}$$

where n is the porosity of the porous media, C_d is the discharge coefficient of the porous media intake, and V is the mean flow velocity. The discharge diverted per unit width is obtained by integrating Eq. (8):

$$q_d = C_d n L_p V \tag{9}$$

where L_p is the length of porous media (index p relates to porous media). Substituting flow velocity from Eq. (7) into Eq. (9), the discharge diverted from the intake finally obtains as

$$Q_d = C_d n L_p B \sqrt{2g\,(y_1 - y_2)} \longrightarrow Q_d = C_d n \frac{L}{\cos\gamma} \times B\sqrt{2g\,(y_1 - y_2)} \tag{10}$$

where $(y_1 - y_2)$ is the water surface difference in the upstream channel and intake channel, g is the gravitational constant, B is the intake width, L is the horizontal length of intake, and γ is the angle which the porous media axis x forms with the horizontal. Equation (10) can be used for bottom intakes with and without surface slope.

3.3 Discharge Coefficient

Dimensional analysis indicates that the physical law governing the outflow along the intake is as follows:

$$F\,(\rho, g, V_1, y_1, n, d_{50}, L, S_p, \mathrm{Re}) = 0 \tag{11}$$

where ρ is water density, g is the gravitational constant, V_1 is the upstream flow velocity, y_1 is the upstream flow depth, n is the porosity of the porous media, d_{50} is the mean diameter of grains, L is the intake length, S_p is the surface slope above porous media, and Re is the Reynolds number. In Eq. (11), the effects of surface tension and fluid compressibility are ignored.

To recognize all the effective parameters in diverted discharge through porous media, y_1, V_1, and ρ are considered as the fundamental variables, and the Buckingham's Π theorem is applied. Therefore

$$C_d = \phi\left(\frac{y_1}{L}, \frac{y_1}{d_{50}}, Fr_1, n, S_p, \mathrm{Re}\right) \tag{12}$$

where $Fr_1 = V_1 \big/ \sqrt{g y_1}$ is the upstream Froude number.

The best nonlinear fit to the data with the coefficient of determination R^2 = 0.918 is found to be

$$C_d = 3.625 \times 10^{-5} \frac{Fr_1^{0.739}\left(\frac{y_1}{d_{50}}\right)^{0.509}}{n^{8.518}\left(S_p + \frac{y_1}{L}\right)^{0.363}} \tag{13}$$

In Fig. 10, a correlation between the calculated and measured C_d values is presented. All of the discharge coefficients of the porous media lie in the range of 0.06 $< C_d <$ 0.14. It should be noted that Eq. (13) is not dependent on Reynolds number, which is, in this case, in the range of 2000 $<$ Re $<$ 6000. Actually, flow in the upstream channel is turbulent.

4. CONCLUSIONS

The bottom intake structures can be used to divert the flow of a steep mountainous river. In this study, an experimental model of a new system of bottom intake with a filled trench of porous media is designed to simulate the hydraulic characteristics of the diverted flow. A large number of experiments under different hydraulic conditions involved a number of variables, namely, discharge, surface slope of the bottom intake, type of granular material, were carried out. The most important results can be listed as the following.

1. By increasing the inflow discharge, the diverted discharge increases too; however, for larger values of the discharge, the ratio of the diverted to the upstream flow approaches a final constant value.

2. Grain size of the porous media has a great influence on the diverted flow. By increasing the grain size, the void spaces of granular material increase, and consequently, the diverted flow increases.

3. By increasing the surface slope of bottom intake with porous media, the entrance angle of streamline to intake will decrease, and thereby the vertical vector of entrance velocity in comparison to horizontal vector will decrease. Because of the horizontal velocity vector increase, most of the flow passes over the intake, and a small percentage of it will divert to the intake channel.

4. The water surface profile depends on inflow discharge, the surface slope of bottom intake, and the porosity of the granular material. Curvatures of the free surface tend to increase with decreasing flow depth and surface slope of bottom intake and with increasing the size distribution of porous media.

5. According to the proposed discharge coefficient, increase of Fr_1 and y_1/d_{50} and decrease of n and summation of y_1/L and S_p lead to C_d increases.

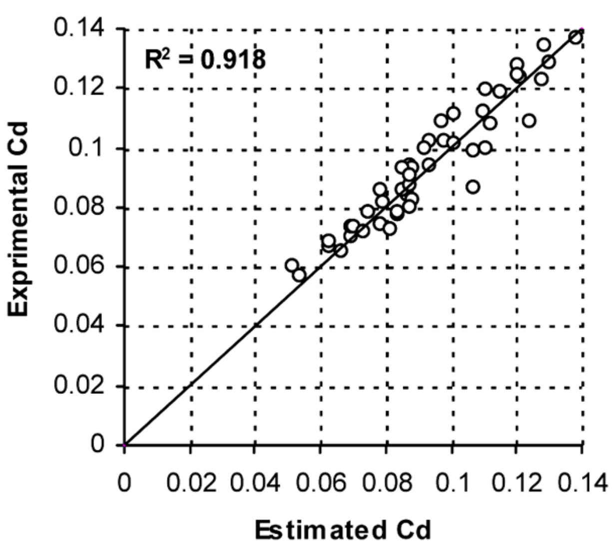

FIG. 10: Comparison between calculated and measured C_d.

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