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Experimental Study on the Adoption of Flushing Technique in Successive Alkalinity-Producing Systems with a Focus on Influence Radius of Orifice

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Research Article

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Abstract

As a successive alkalinity-producing system pond for purifying mine drainage is operated, sediment accumulates in the limestone layer of the pond, and as the amount of accumulated sediment increases, the water permeability and treatment efficiency of the pond decrease. Hence, a flushing system is required, comprising of a network of perforated pipes installed in the limestone layers, to periodically discharge sediment and mine drainage to the outside. The performance of a flushing system depends on four distinct characteristics of the system: the characteristics of the limestone layer, the sediment, the flow, and the flushing device. However, existing studies have evaluated the performance of the entire system without considering these conditions. In this study, a new experimental method for designing a flushing system is proposed. This method is based on an experiment to evaluate the influence radius of orifice, which is the radius of the spherical volume around an orifice that can suck sludge by flushing. The results showed that the flow rate of water through the orifice in the glass bead layer matched well with the Blake–Kozeny formula, and that the greater the diameter of the orifice, the greater the influence radius of orifice. The influence radius of orifice according to the diameter and spacing of the orifice was evaluated, which provides a key criterion for designing a flushing system.

Introduction

A successive alkalinity-producing system (SAPS) is a pond that biologically and chemically treats acidic mine drainage (AMD). A SAPS is a passive treatment method that naturally purifies mine drainage. A SAPS consists of layers of water, organic matter, and limestone, as shown in Fig. 1. Acid mine drainage flows into the water layer and passes through the organic and limestone layers in sequence (Kepler and McCleary 1994). In the early stages of operation of a SAPS, the purification efficiency of mine drainage is high, but over time, the deposits accumulated in the organic matter layer and limestone layer cause the efficiency to gradually decrease.

A SAPS pond is generally designed to provide sufficient alkalinity to operate for 20–25 years (Zipper 2001), but if the sediment accumulated in the layer cannot be removed effectively, the lifespan is inevitably shortened. To solve this problem, a flushing technique was developed, in which a network of perforated pipes installed in the limestone layers is opened regularly to discharge sediment and mine drainage to the outside (Weaver et al. 2004).

Various field experiments have been conducted to determine the application conditions of an effective flushing system in SAPSs (Watzlaf et al. 2002; Lagnese et al. 2002; Rose et al. 2004), resulting in improvements to the flushing system and their better performance.

The performance of a flushing system depends on the following four parameters:

- - Characteristics of the limestone layer: shape and size distribution of particles, arrangement of particles, effective porosity, and water permeability in the limestone layer.

- - Characteristics of the sediment: amount, distribution, hardness, density, etc.; these affect the separation of sediment by local velocity of AMD and the permeability of the limestone layer.
- - Flow characteristics of the SAPS: because the energy required for flushing is the difference in the water head between the water surface and the flushing system, and because the amount of energy varies depending on the flow conditions, the flow characteristics of a SAPS such as the water head, inflow rate of mine drainage, permeability of the organic layer, and so on should be considered.
- - Characteristics of the flushing device: the flushing performance varies with the diameter, spacing, and arrangement of orifices drilled into the pipe, as well as the diameter and arrangement of pipes that constitute the flushing system.

However, existing studies have evaluated the overall performance of the system through experimentation without distinguishing the factors that affect the flushing. However, to improve our understanding of the mechanism of the flushing system and to accurately evaluate and predict the flushing system, a process of classifying the characteristics that affect the performance as described above and integrating them into a design is required.

In this study, the limestone layer characteristics, sediment characteristics, and flow characteristics were given the same conditions by using the same glass beads with regard to their shape and size, sediment, and experimental conditions, respectively, and the effect of the characteristics of the flushing device on the flushing was evaluated. This allowed for an evaluation of the effect of orifices on flushing, and whether the influence radius of orifice proposed in this study is applicable to the design of the flushing system.

Materials And Methods

Design and manufacture of the experimental apparatus

In order to consider only the characteristics of the flushing device, the same characteristics of the limestone layer were ensured by using glass beads of the same shape and size; further, this aspect with regard to the sediment was ensured by using sediment having the same density, amount, and the origin of its production, in the experiment. In addition, to establish the same flow characteristics as the SAPS, the conditions of natural drainage under a constant head without an inflow rate were used in the experiments.

A schematic diagram of the experimental apparatus is shown in Fig. 2. The dimensions of the apparatus are as follows: 1 m length, 0.5 m width, and 1.2 m height. Several pipe connections and valves were installed in the tank. The pipe connection is a device that facilitates the changing of pipes, and three of these were installed in the tank at a spacing of 0.33 m; on/off valves were also installed. On the right side of the tank, a valve for drainage was installed, and a transparent plate and a scale were installed to check the water level and observe the flow situation in the tank.

To simulate the limestone layer of a SAPS with glass beads, a glass bead layer with an average thickness of 19 cm was laid above the pipe. The glass beads had a spherical shape and were 20 mm in diameter, as shown in Fig. 3. The porosity of the glass bead layer was found to be an average of 39.0%, which is similar to the porosity of 39.70%±1.24% in orthorhombic packing (Alberts 2005).

In this study, three cases were set for each factor to understand the effect of orifice size and spacing and pipe diameter on the flushing effect. The pipe used in the experiment was a commercial polyvinyl chloride (PVC) PVC pipe with a diameter of 16 mm, 50 mm, and 50 mm. The diameter of the orifice was 3 mm, 6 mm, and 9 mm, and the orifice spacing (OS) was 100 mm, 200 mm, and 300 mm.

The sediment used in the experiment was the mine drainage sediment produced at the Hwangji-Yoochang passive treatment facility located in Samcheok city, South Korea. The main component of this sediment is iron oxide, and the dry density of the sediment is 3.85 g/cm^3. The photograph of the sediment and the particle size distribution of the sediment used in the experiment are shown in Fig. 3 (a) and Fig. 3 (b). The density of the sediment was measured using pycnometers with capacities of 25 ml and 50 ml, and the particle size distribution of the sediment was measured with Malvern Mastersizer 3000. For each experiment, the same dry weight of sediment was mixed with water and put into the water-filled tank, and the experiment was carried out after the sediment had completely settled. By this process, the sediment was uniformly distributed within the layer of glass beads (Fig. 3 (c)).

Experimental method

Flushing involves the installation of a network of pipes with orifices in the limestone layer of the SAPS, which is filled with water at a constant height, and the removal of the sediment that accumulates in the limestone layer using water by rapidly opening the valve connected to the pipe. The experimental procedure was as follows.

1. Install a pipe with the orifice facing upward at the bottom of the tank, and lay glass beads in a layer 19 cm thick.
2. Close all valves in the tank and fill it with water to 1.03 m.
3. Mix 740 g dry weight of sediment with water and evenly sprinkle it on the surface of the water.
4. Wait for the sediment in the tank to settle completely to the bottom.
5. Place the bucket in the discharge area. Open the valve rapidly and close the valve when the water level in the tank reaches 0.95 m.
6. Measure the volume of the mixture recovered in the bucket, and then weigh only the sediment.
7. Repeat the above procedure by varying the spacing of the orifices and the pipe diameter.

The amount of the recovered sediment was evaluated by measuring its weight after drying it in a dryer at 80 °C.

During this experiment, the discharge flow rate was first checked for consistency with the existing theoretical models, such as Bernoulli formula and Blake–Kozeny formula, by draining only the water in the tank, and then the experiment from step 3 was performed after putting the sediment in the tank.

Evaluation of water flow rate in limestone layer

The limestone layer in a SAPS resists the flow of mine drainage. The magnitude of the flow resistance in the limestone layer can be assessed indirectly using the discharge flow rate when flushing is performed. Therefore, it is important to check the discharge flow rate by flushing under a certain water head condition. In this study, it was relatively easy to predict the discharge flow rate because glass beads of spherical shape and uniform size were used instead of limestone (which has particles with irregular shapes and of various sizes).

The flow velocity in a pipe installed at the bottom of the tank filled with water to a constant height is generally expressed by the Bernoulli equation, as shown in Equation 1.

See equations 1 and 2 in the supplementary files.

Conceptual suggestion for the influence radius of orifice

The velocity distribution around the orifice is important in removing sediment by flushing. This is because if the magnitude of the flow velocity around the orifice is large enough to move the sediment, the sediment can escape out of the pipe with the water, and if the velocity is small, the sediment remains stationary.

Singh et al. (2020) studied the flow phenomenon that occurs when a pipe sucks in the surrounding fluid, which is similar to the phenomenon of an orifice sucking water in a limestone bed. They presented the velocity distribution when a small pipe sucks in the surrounding fluid, as shown in Fig. 4. If the Reynolds number (Re) is small (Fig. 4 (b)), the volume representing the same flow velocity shows a long ellipsoid in the direction of flow; when the Reynolds number is large (Fig. 4 (a)), the ellipsoid is distorted perpendicular to the direction of flow.

In the initial stage of flushing, the flow velocity is high due to the high water head above the orifice; it decreases over time as the head is lowered. Thus, the velocity distribution around the orifice varies over time but can be assumed to be close to a sphere on average. This velocity distribution shape has the same shape if the porous medium is homogeneous. Based on this, this study assumes that the volume where sediment is removed by the orifice during flushing is in the shape of a sphere.

If sediment is uniformly distributed in the glass bead layer, the volume of sediment removed by an orifice can be calculated from the amount of sediment removed by flushing. In this study, the influence radius of orifice R_I refers to the radius of the sphere when the volume of sediment removed from the porous medium by one orifice is assumed to take a spherical shape, which allows an evaluation of the effect of flushing. It is described by the formula as follows.

See equation 4 in the supplementary files.

However, depending on the flow conditions, such as the hydrostatic head, inflow rate, and orifice diameter (OD), the shape of the velocity distribution around an orifice during flushing may not take the shape of a sphere.

Experimental Results And Analysis

Comparison of orifice flow rate between theoretical equations and experimental results

Fig. 5 shows a comparison of the flow rate according to the diameter of the orifice in the absence of a glass bead layer in the water tank. As shown in the figure, the measured flow rate and the flow rate calculated by the Bernoulli equation are relatively well-matched. When the number of orifices is increased to two, the flow rate is also doubled.

Fig. 6 illustrates the relative error between the flow rates under conditions using the glass bead layer versus without the layer in the tank. The relative error of the flow rate in the Blake–Kozeny formula is 6.9% lower for all ODs when the glass bead layer is used than the relative error without the layer. This is because the glass bead layer acts as a flow resistance when water flows through the orifice. The experimental results show dispersion, which can be attributed to the arrangement of the orifices and beads in the experiment and overall similarity of the results to those of the Blake–Kozeny model.

The flow rate of water passing through the orifices in the pipe is constant regardless of the diameter of the pipe. This is because the cross-sectional area of the pipe is larger than the sum of the areas of the orifices. As the number of orifices increases, the amount of water flowing into the pipe increases, so the diameter of the pipe should be considered when selecting the number of orifices. **See equation 3 in the supplementary files.**

Flushing performance evaluation of an orifice in the glass bead layer

In this experiment, water was drained through the orifice of the pipe until the water surface in the tank reduced to a constant height; this implies that the water pressure acting on the orifice is highest during the initial stage of the experiment and decreases over time. Consequently, the amount of water and sediment discharged from the orifice is initially at a maximum and gradually decreases. In addition, the time (tens of seconds to minutes) required for the discharge of water decreases as the diameter of the orifice increases. The large discharge flow rate means that the velocity of water flowing through the glass bead layer is high, so sediment in the layer is more easily removed. This also means that the volume of water from which the sediment is removed increases; thus, R_l also increases.

Fig. 7 illustrates the R_l according to the OD derived from the experiment. As mentioned earlier, it is evident that R_l increases with an increase in the OD. Further, the rate of R_l increase when the OD of 5 mm or more is smaller than the rate of increase when the diameter of 5 mm or less.

Fig. 8 shows the R_I measured according to the OS; as the spacing between orifice increases, the R_I increases and becomes almost constant. This means that under a constant head condition, the extent to which the OS can affect R_I is limited. This is because, as shown in Fig. 9, when the OS is narrow, two orifice influence volumes overlap with each other, and as the orifice gap gradually widens, the overlapping influence volumes separate from each other.

The smaller the OD, the smaller the orifice influence volume, so the overlapping influence volumes are separated at a relatively narrow OS. On the other hand, when the OD is large, the orifice influence volume is large, so the overlapping influence volumes of orifice are separated at a relatively wide OS. Fig. 9 shows the maximum R_I, which is the maximum radius that one orifice can affect, as a function of OS. Under the experimental conditions at point C, the maximum R_I for ODs of 2.5 mm, 5 mm, and 7 mm were 3.2 cm, 5.3 cm, and 6.1 cm, respectively.

Design approach of the flushing system by orifice influence radius

Under the experimental condition indicated by point C in Fig. 9, the maximum OD was 7 mm, R_I was 6.1 cm, and diameter of the sphere-shaped influence volume of orifice was 12.2 cm. Thus, the OS should be smaller than 12.2 cm for the effective removal of sediment from the glass bead layer. This result is meaningful in terms of providing important guidelines for setting the OS, which is a key factor in designing a flushing system.

When OD and OS are determined based on the structure of the SAPS, the number of orifices and the required flow rate of water through an orifice can be calculated by considering the volume of the layer. After the number of orifices and the inflow rate are determined, the diameter of the pipe connected to an orifice can be selected, and the pipe can be arranged in the layer. Via this process, a flushing system can be designed conducive for operation in the limestone layer.

Conclusions

The results of this study are summarized as follows:

- In this study, the factors influencing the performance of the flushing system were classified into four categories: limestone layer characteristics, sediment characteristics, flow characteristics of the SAPS, and flushing device characteristics; only the latter was evaluated herein.

- The R_I suggested in this study refers to the radius of the sphere when the volume of sediment removed from the porous medium by one orifice is assumed to take the shape of a sphere, which allows the evaluation of the effect of flushing.

- The experimental results show that the flow rate of water through the orifice in the glass bead layer matched well with the Blake–Kozeny formula, and that the greater the diameter of the orifice, the greater the R_I. This is because as the OD increases, the flow rate of water through the orifice increases, so the velocity of flow through the glass bead layer also increases.

- The R_I is small when the OS is narrow, but it increases as the OS gradually increases, and then becomes constant. This is the process by which the overlapping influence volumes of orifice separate from each other, as shown in Fig. 9.

- Under the experimental condition denoted by point C in Fig. 9, the maximum R_I for an OD of 7 mm was 6.1 cm. This represents the maximum distance over which one orifice can remove sediment from the layer; thus, the OS should be less than twice the R_I.

- This result is meaningful for providing important criteria for setting the OS, which is a key factor in designing a flushing system. The methodology presented in this study can be helpful in identifying the main factors that affect a flushing system thereby improving their design and efficacy.

Declarations

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Conflicts of interest/Competing interests (include appropriate disclosures)

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Availability of data and material (data transparency)

Not applicable

Code availability (software application or custom code)

Not applicable

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Figures

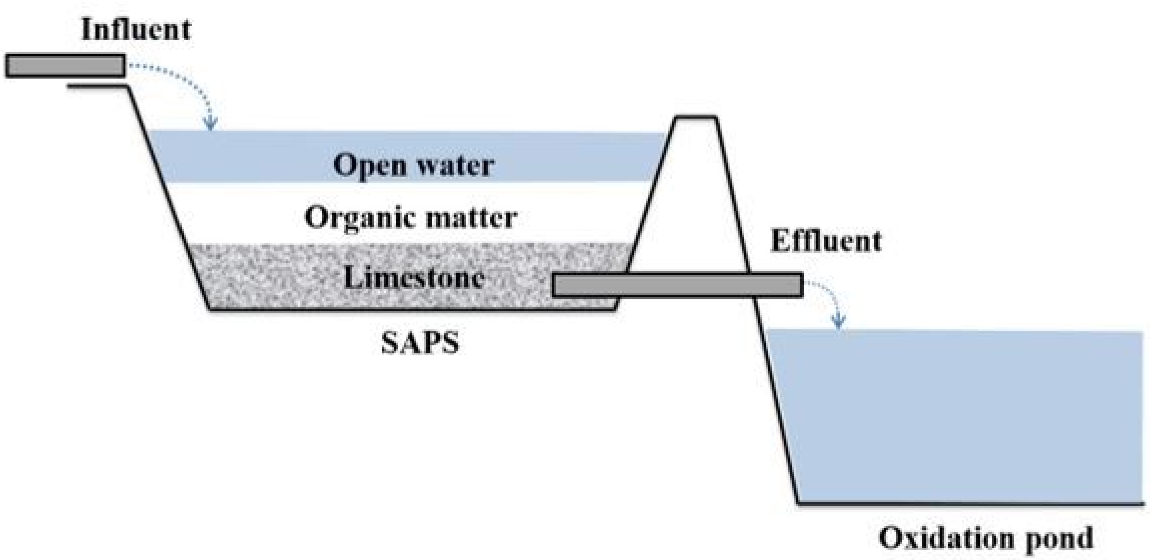

Figure 1

Structure of a SAPS pond

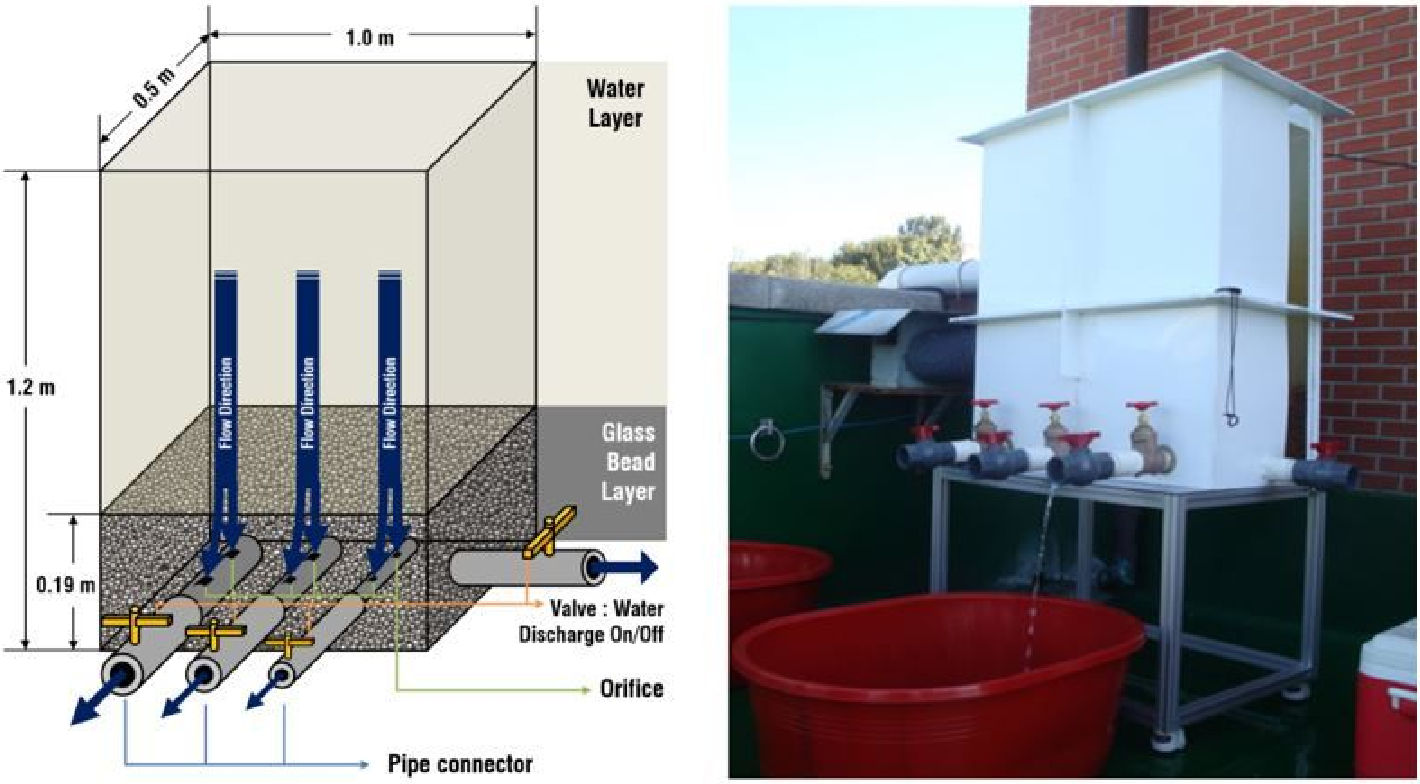

Figure 2

Schematic diagram and photograph of the flushing experiment apparatus

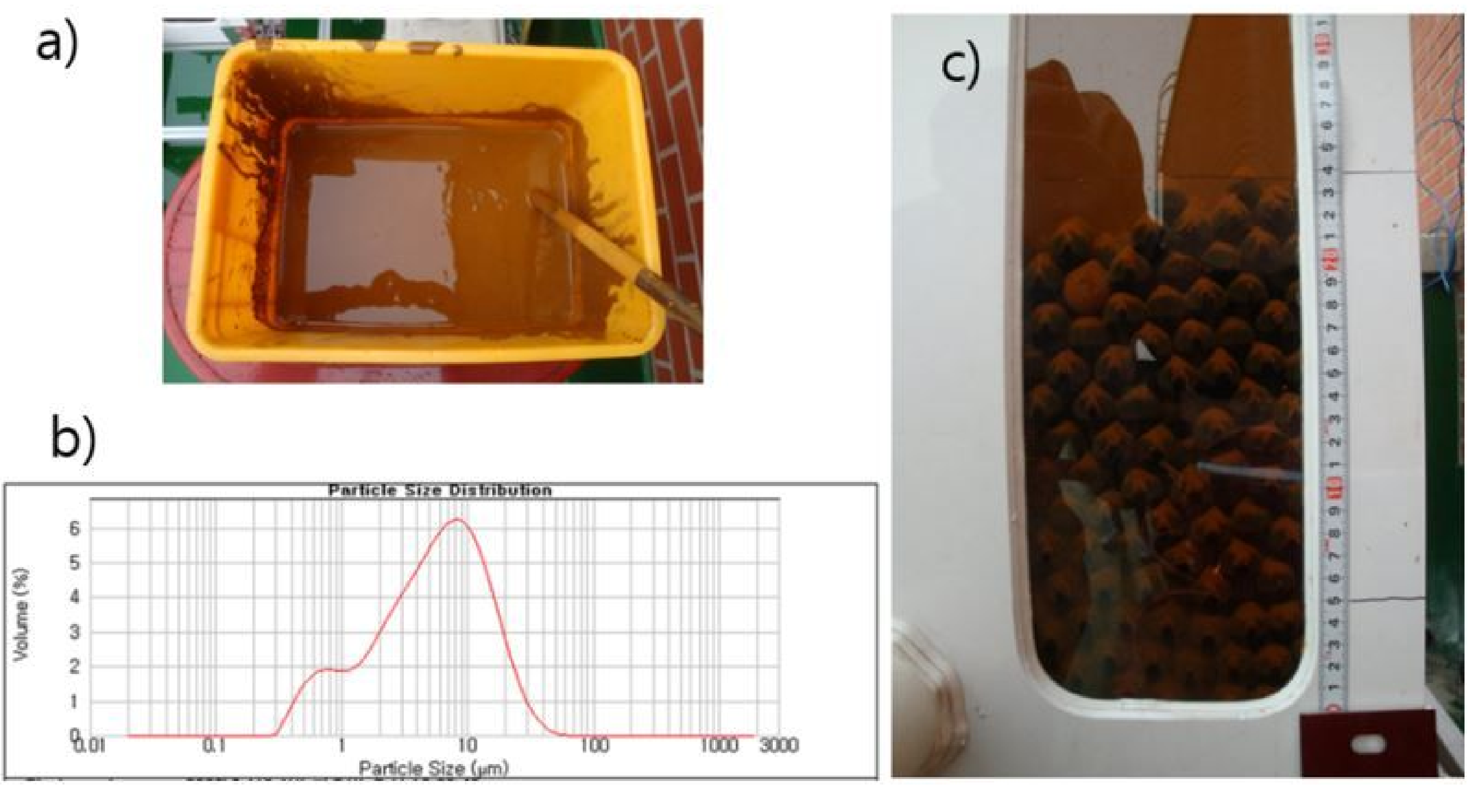

Figure 3

Sediment used in the experiment (a), the particle size distribution of the sediment (b), and the distribution of the sediment in the glass bead layer (c)

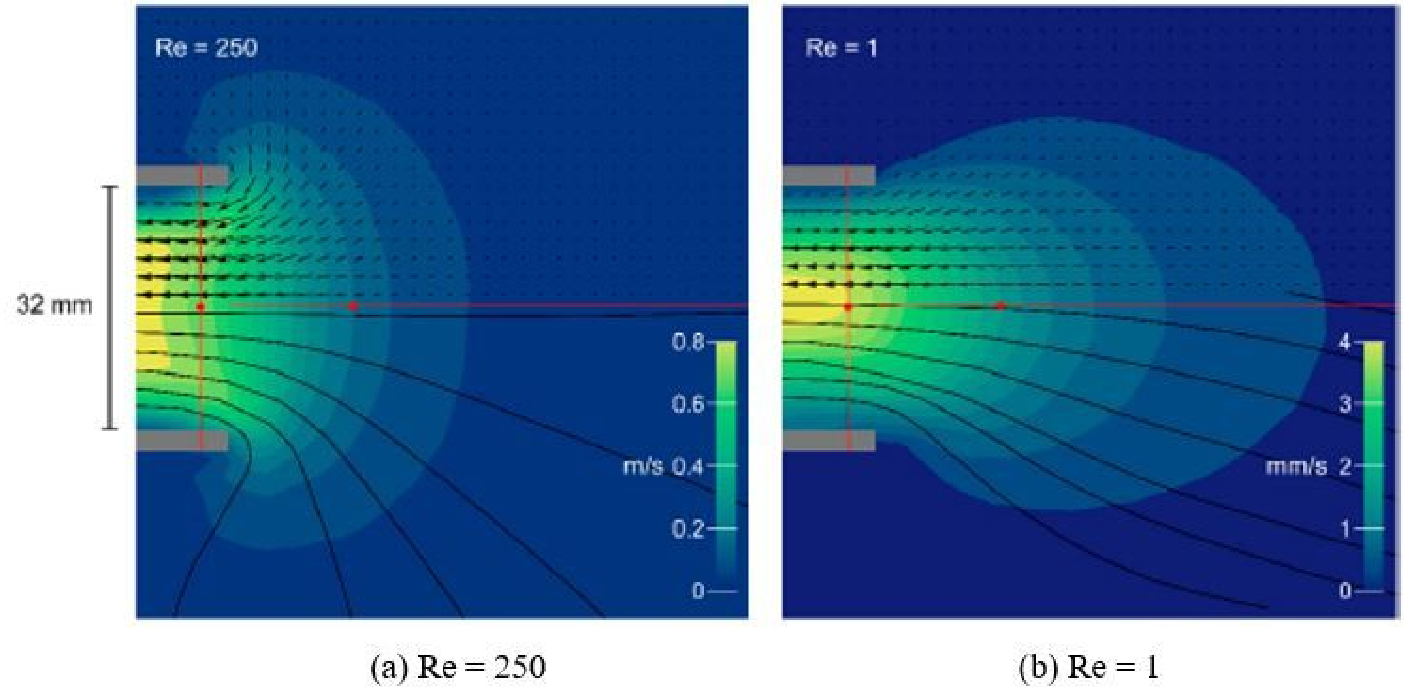

Figure 4

Distribution of flow velocity and streamline according to Reynolds number (Singh et al. 2020)

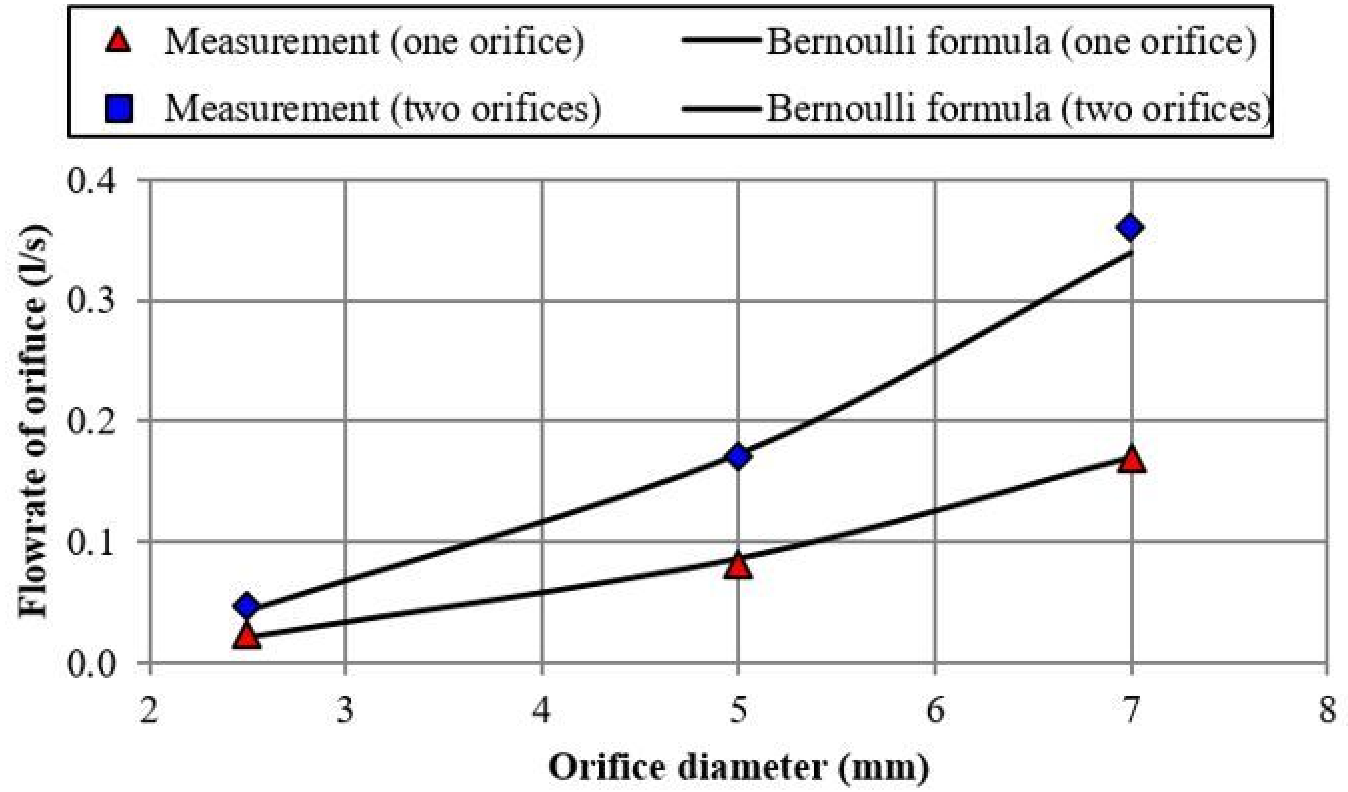

Figure 5

Flow rate according to the diameter of the orifice without the glass bead layer

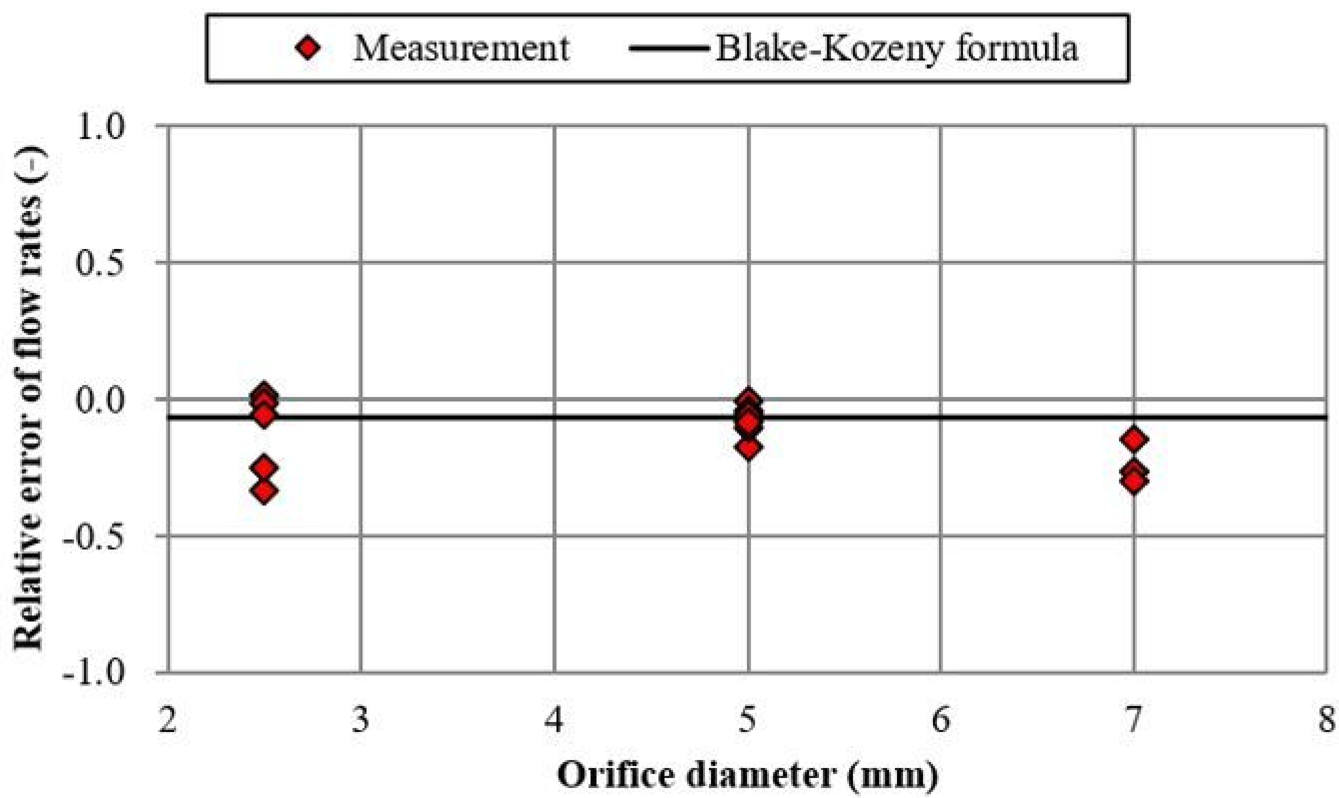

Figure 6

Comparison of relative errors in flow rates with and without the glass bead layer

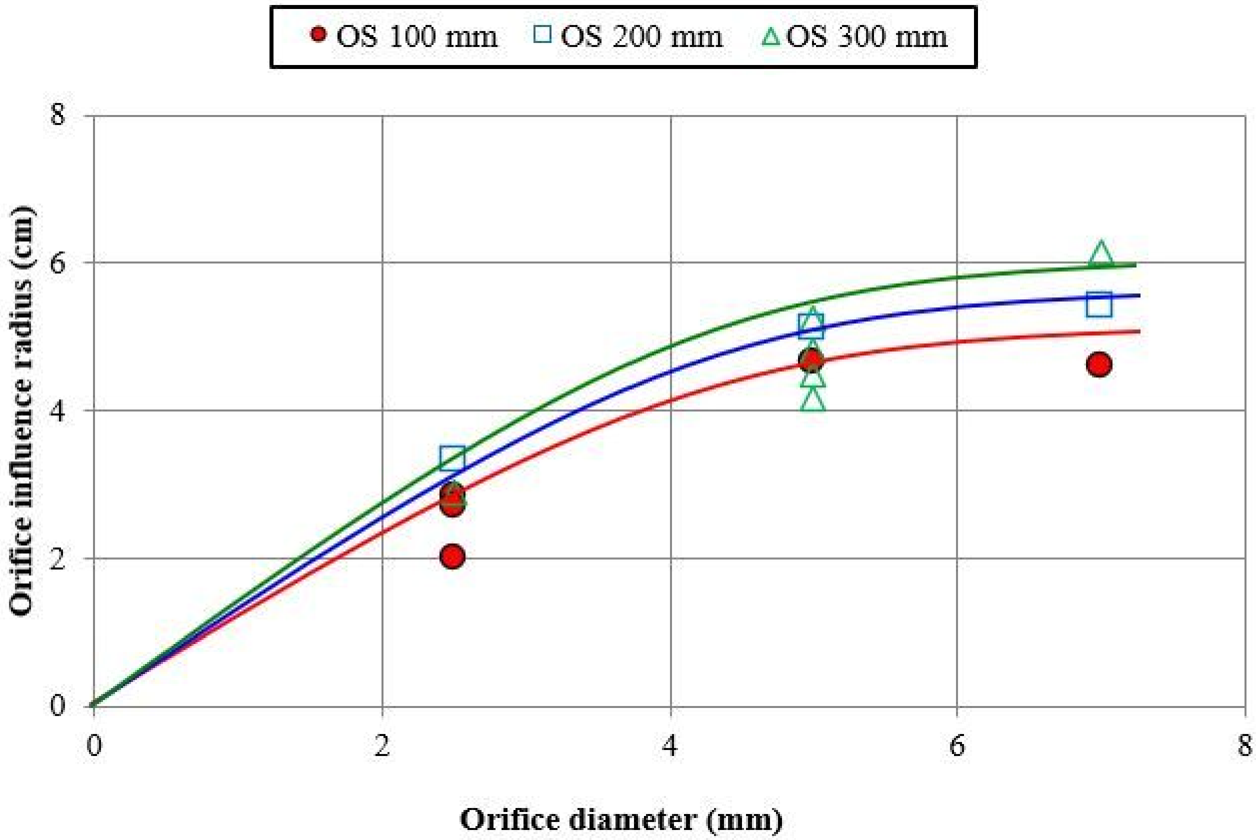

Figure 7

Influence radius of orifice according to orifice diameter

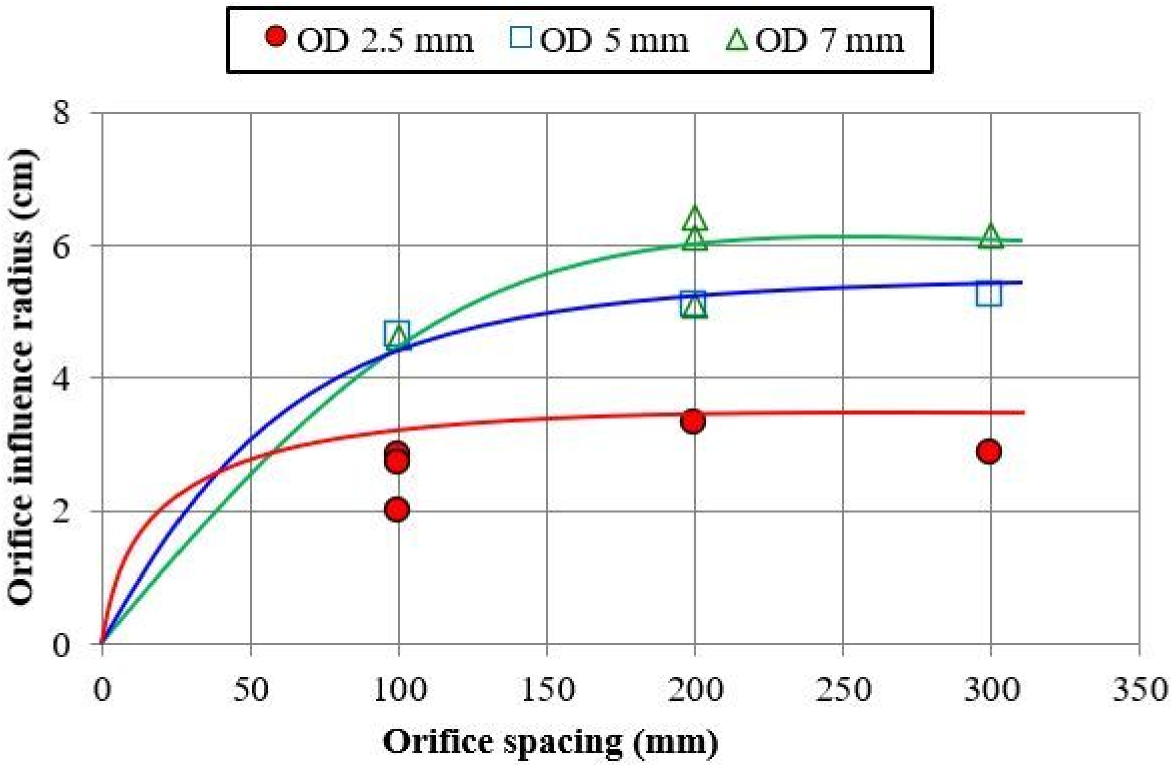

Figure 8

Influence radius of orifice according to orifice spacing

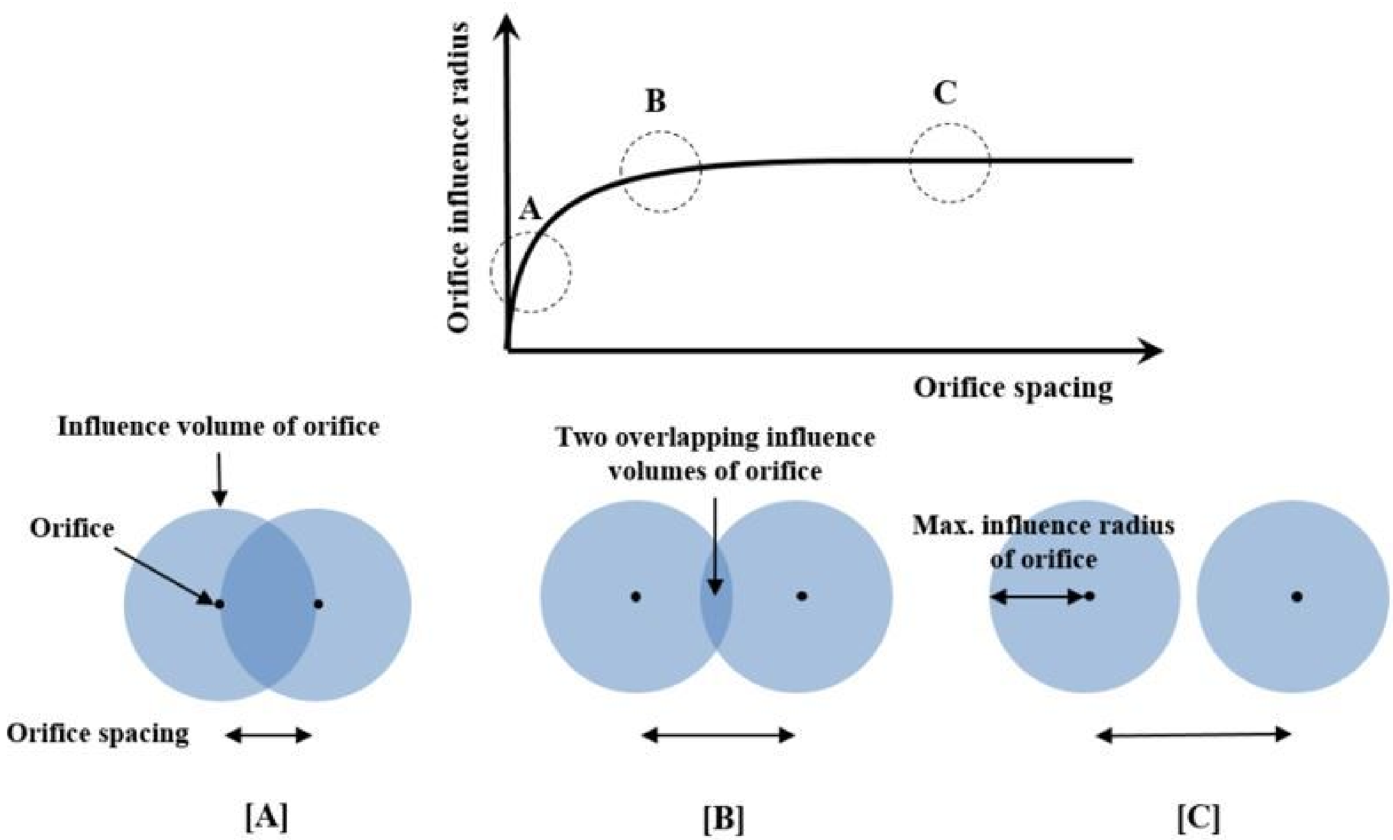

Figure 9

Orifice influence volume according to orifice spacing

Supplementary Files

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