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Research article

Deposition regularity in a rainwater pipeline based on variable transport flux

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ABSTRACT

Experiments of the deposition of suspended particles in a rainwater pipeline were combined with mathematical model fitting to explore deposition regularity under variable transport flux. The simulation results showed that four primary factors affected deposition regularity in a rainwater pipeline. In particular, the deposition and flushing processes alternately dominated when the flow and initial suspended solids (SS) concentration changed simultaneously. The migration of the easy deposition position (EDP, the position with the largest deposition velocity) displayed an obvious regularity, shifting from front to back along the pipe regularly at increasing flow, and from back to front when flow decreased.

1. Introduction

The deposition and migration of suspended particles is an integral part of the study of sedimentation in drainage pipes. It is important that this deposition and migration process be fully understood and quantified to aid in improving the planning, design, construction, and operation of these pipes to improve or solve the potentially serious problems caused by deposition.

Research results on the transport regularity of suspended particles or sediments in drainage pipelines have been previously reported, and can be classified into two main areas. In the first type, models and algorithms have been applied for calculating migration velocity or Froude number (Fr) to simulate the migration of suspended particles or sediments in pipelines. A mathematical model was established to determine the migration regularity of pipeline sediments where pipeline boundary conditions and other factors were considered (Ab Ghani, 1993). The transport regularity of sediment in pipelines was simulated over time using an artificial neural network (Ebtehaj and Bonakdari, 2013). A two-dimensional bed-load transport numerical simulation was applied for sewage and channel (Caviedes-Voullième et al., 2017). After a numerical approach was used to tackle the difference between river and sewage in an efficient way, the results showed that the approach was accurate and applicable for sewage and channel flushing problems. A method was presented for determining the conditions under which large solids were able to move in a pipe, where their movement depended primarily on a dimensionless solids buoyancy number, Fr, or velocity (Walski et al., 2009). In addition, genetic programming (Aytek and Kisi, 2008) and gene expression programming (Ab Ghani and Azamathulla, 2011) have been used for simulating the movement of suspended particles or sediments in pipelines.

In the second area of researches, a reasonable determination of the design velocity in pipes and channels can avoid the occurrence of sedimentation. There have been some studies concerning the limiting velocity or critical velocity in pipes and channels. An adaptive neuro-fuzzy inference system was presented to predict the functional relationships of sediment transport in sewer pipe systems, and the model successfully calculated the limiting velocity in storm sewers (Azamathulla et al., 2012). Sediment particle and sphere velocity measurements were carried out in two pipe channels, and a semi-theoretical equation was established for sediment transport at the limit of deposition in sewers (Ota and Perrusquía, 2011). A self-cleansing model was developed to determine the non-deposition particle Fr value for bed load sediment transport, and it showed a wide range of applicability in terms of different channel cross-sections (Safari et al., 2017). Experimental studies were carried out in five channels with different cross-sections to calculate the deposition velocity, and concluded that the design velocity depended on the shape of the channel cross-section. Rectangular and V-bottom channels needed lower and higher incipient deposition velocities, respectively (Aksoy et al., 2017). To determine the effect of sediment deposition thickness on the critical velocity for incipient motion, a multiple linear regression analysis was performed by incorporating thickness ratios, which could predict critical velocity

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for both loose and rigid boundary conditions (Bong et al., 2016).

Under rainfall conditions, the flow and concentration of suspended particles in rainwater and combined sewer systems vary greatly. At present, only a small amount of researches on the deposition process under variable flow or variable concentration have been carried out by monitoring actual pipelines. The raw acoustical turbidity was used as an online monitoring tool, and the accurate suspended solids concentration and water height could be obtained through this approach (Pallarès et al., 2016). A new technique was developed for long term monitoring of sediment height within a combined sewer, and the muddy layer presented a daily dry weather pattern, which reflected the flow hydraulics (Larrarte et al., 2016). Sonar was used to investigate the morphology of sediments in sewer networks. It was found that rainfall events would remove the sediment stack and cause its subsequent renewal, which also influenced the bio-physicochemical conditions in the sewer (Carnacina et al., 2017). The flush-related transport/deposition processes of a large combined sewer were monitored in Paris, and the flush had a different impact on the various sediments in the bed mixtures (Shahsavari et al., 2017). A pilot experiment was performed in a test channel using real wastewater and rainwater, and the continuous change between deposition and flushing led to the state of balance (Lange and Wichern, 2013).

The above efforts have studied the deposition and flushing processes in drainage pipelines mostly by establishing models or conducting long-term monitoring of actual pipelines to determine deposition regularity. However, the deposition characteristics of different positions (front, middle, end, etc.) of the pipeline have not been reported. By comparing the deposition velocity of different positions in the pipeline, the most serious deposition position can be determined, a position referred to as the easy deposition position (EDP). In addition, laboratory simulations of the deposition process in a pipeline under variable flow and variable initial suspended solids (SS) concentration are relatively rare, and there are few calculations for parameters such as deposition velocity and EDP under variable flow or concentration conditions.

Since the actual rainfall process is too complicated to easily simulate, it is beneficial to simplify this input by assuming that the change in rainfall intensity exhibits a given regularity: increase, decrease, increase first and then decrease, or decrease first and then increase. Correspondingly, the flow into the rainwater pipeline would follow the same rule. The concentration of particles carried by the rainwater would then also follow a similar regularity to the one used to describe the rainfall above. This simplification is valid since these situations represent most of the rainfall patterns.

In this paper, the deposition regularity of suspended particles in a rainwater pipeline under variable transport flux is analyzed from a macroscopic point of view. That is, deposition regularity is analyzed based on the variable flow, the variable initial SS concentration, or the additive effect of both. Through laboratory experiments and mathematical model fitting, the deposition characters of suspended particles in different positions—the front, middle, posterior, and end segments—of a pipe are compared, and the reveal of the deposition regularity in different positions is one of the innovative points of this work. The deposition velocity is calculated, and the migration regularity of the EDP is obtained. This migration regularity of the EDP in rainwater pipelines under variable transport flux is the other innovative point of this work.

2. Materials and methods

2.1. Reactor

The device used for testing suspended particles deposition in a rainwater pipeline is illustrated in Fig. 1. The pipe is Plexiglass with the length of 12 m and a diameter of 150 mm. The test pipe is connected to the bottom of a water tank, with sampling holes in the pipe at intervals of 1 m. Each sampling hole is connected to a rubber hose with an inner diameter of 6 mm, and each hose is clamped with a water stop clamp. During sampling, the water stop clamp is released. For our experiments, we used the sampling holes located at 1 m, 5 m, 8 m, and 12 m along the pipe, corresponding to the front, middle, posterior, and end segments of the pipeline, respectively. A suspended solution of a mixture of Kaolin and water was stored in the water tank and constantly stirred. The pipe flow was controlled through the valve and flow meter at the beginning of the pipe. At the beginning of the test, the valve was opened to a certain flow level and sampling was conducted when the flow of the pipe was in a stable state. The valve opening was then changed to another flow and sampled, and the same sampling method was used for each flow. This process simulated the state of variable flow in an actual rainwater pipeline (Fig. 1(a)). For the SS measurement, the standard method using filtration and weight determination was used with blanks measurements (Bersinger et al., 2015).

To simulate the variable concentration and additive effect, three water tanks were used to hold the high, medium, and low SS concentrations, respectively, to achieve different initial concentrations of suspended particles (Fig. 1(b)). The three concentrations were 250 mg/L, 150 mg/L, and 50 mg/L, respectively. The selected concentrations were based on site observations (Park et al., 2010; Kamei-Ishikawa et al., 2016) (Table 1).

2.2. Mathematical modeling

Based on the experimental and computational data, the principles and the methods of fluid mechanics and probability statistics were used in this work. The mathematical models describing the sedimentary process were built using Matlab 9.0 (R2016a). Through statistical analysis and data fitting, the empirical formulas for calculating the deposition velocity in a rainwater pipeline under variable flow and variable initial SS concentration were established.

$$V = f(Q) \tag{1}$$

$$V = f(C_0) \tag{2}$$

Here, V is the deposition velocity, Q is the flow in the pipe, and C_0 is the initial SS concentration.

Using the flow and SS concentration of the water samples, the deposition velocity (V_i) at a given position in pipe can be calculated using

$$V_i = \frac{(C_0 - C_i)Q_i}{3600} \tag{3}$$

Where V_i is the deposition velocity of the i-th sampling hole (mg/s), C_i is the SS concentration of the sample from the i-th sampling hole (mg/L), and Q_i is the flow of the i-th sampling hole (L/h).

3. Results and discussion

3.1. Deposition process in a rainwater pipeline under variable flow

The deposition process of suspended particles in a rainwater pipeline was studied under four different variable flow states: increasing, decreasing, first increasing and then decreasing, and first decreasing and then increasing. The selection of the parameters for this study was based on a previous study by Liu et al. (2018) and data from the literature (Table 1). The parameters in this work were set as follows: flow varied from 100 L/h to 550 L/h, and initial SS concentration (C_0), pipe slope (i), and particle size (d) were 100 mg/L, 0.003, and 6 μm, respectively. Note that, the flow selected in the study of deposition process in rainwater was lower than that listed in Table 1, for the flow listed in Table 1 was required for flushing.

The deposition velocities at the front, middle, posterior, and end segments of the pipe, respectively, for each of the four types of variable flows are shown in Fig. 2. As the flow increases from 100 L/h to 550 L/h, the deposition velocity at the different positions along the pipe