Analysis and calculation of sediment scouring rate at different locations of storm sewer

Cuiyun Liu*, Wenke Lv, Qi Liu, Jie Zhou, Yiyang Wang, Xiaohua Zhang and Jun Zhou
College of Urban Construction, Nanjing Tech University, Nanjing 211816, China

*Corresponding author. E-mail: yunduobai@126.com

ABSTRACT

To explore the migration differences of sediments at the front, middle, and end sections of a storm sewer when scoured by water, and further evaluate the pollution load, the scouring process of sediments at different locations of a storm sewer was simulated and mathematical models were built to calculate the scouring rate. Results show that scouring rate is affected by sediment particle size, pipeline slope, sediment thickness, and water flow velocity. As the slope increased, scouring rate at the end section increased more obviously. The scouring rate at the front section slightly decreased with increasing sediment thickness, but opposite trends were observed at the middle and end sections. When the particle size (0.33 mm–0.83 mm) and flow velocity (0.15 m/s–0.65 m/s) increased within their ranges, scouring rate increased across all three locations. Models for calculating scouring rate were established via two data fitting. The calculated values were compared with measured values at a scouring time of 1 min. Under different particle sizes, the difference between the calculated and measured values at front, middle, and end sections were in the ranges of −0.63% to 0.63%, −0.01% to 0.02%, and −0.13% to 0.16%, respectively, all of which showed good consistency.

Key words: calculation model, scouring rate, sediment, storm sewer

HIGHLIGHTS

• The increase of scouring rate at end section is more obvious as slope increases.
• Scouring rate of all the three locations increases with flow velocity increasing.
• Scouring rate is great when particle size is big ($d_{50} = 0.33–0.83$ mm).
• Scouring rate at different locations in a storm sewer is calculated using models.
• Difference between the calculated and measured values is from −0.63% to 0.63%.

INTRODUCTION

Urban drainage pipelines are important parts of an urban drainage system where suspended solids are usually deposited. Sediments in these pipelines are easily scoured and re-suspended under the influence of water flow, and an alternating process of scouring and depositing usually takes place (Memarian & Balasundram 2012). Pollutants produced by scouring, entering the receiving water body or sewage treatment plant will cause some environmental problems. Research by Bertrand-Krajewski et al. (2006) showed that the scouring and resuspension of pipeline sediment would increase the concentration of runoff pollutants, of which SS and COD account for 60%. Therefore, the quality of the receiving water body deteriorates. At higher flow rates, large particles of pollutants in pipeline sediments tend to be scoured away, thereby increasing the organic content in the sewage and affecting the quality of the influent water in the sewage treatment plant (Xue 2020). A material exchange also occurs between sewage and sediment in pipelines, and the physical deposition process would reduce the content of organic nitrogen, phosphorus, and other pollutants in the sewage by more than 70% (Shi et al. 2018).

To solve these pollution problems, the rules of sediment scouring and transportation in urban drainage pipelines should be mastered, the sediment scouring process should be analyzed, and the contribution of sediment scouring to downstream pollution in the pipeline should be calculated.

Some progress has been made in analyzing the migration characteristics of sedimentary particles in drainage pipelines. Studies on the deposition and scouring of particle sediments revealed that the sedimentation effect of particulate pollutants

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at low flow rates was greater than the scouring effect, but the opposite was observed at high flow rates (Sang et al. 2017). The small particle pollutants had a relatively strong cohesive force, and the aggregates formed by these pollutants had strong erosion resistance (Liu et al. 2021). After analyzing the movement of sediment in sewers, a recommended design guidance had been summarized for the sewer designing (Butler et al. 2003). Some mathematical models have also been established to simulate the migration process of sediments. For instance, Schellart et al. (2008) performed a Monte Carlo simulation to predict the migration of actual pipeline sediments. Yu used the pipeline sediment load model to estimate the pipeline sediment load of the sewage collection system in the main urban area of Nanjing (Yu 2015). A mathematical model was also built to calculate the scouring rate and flux of storm sewer sediments under specific conditions (Liu et al. 2019). To check the erosion of mixed organic/granular sediment in-sewer deposits, a model was used to simulate the interaction mechanisms between the granular particles and the fine-grained organic sediments (Rushforth et al. 2003). Saul et al. (2003) described the movement of deposited cohesive-like sediment beds in sewers, and confirmed that process models had the potential to describe the temporal pattern of transport rate and concentration of the suspended sediments. Banasiak & Verhoeven (2008) quantified the mobility behavior of cohesion affected sediments by a test on partly cohesive mixtures and a fine, uniformly graded sand conducting in a semicircular pipe.

Studies on sediment scouring across different locations of a drainage pipeline have produced useful results. When the pipeline flow increases, the maximum deposition point (i.e., the position with the largest amount of deposition in a section of the pipeline) of suspended particulates move from the front section of the pipeline to the middle and end sections in turn. However, when the pipe flow decreases, the opposite is observed (Tan et al. 2019). Some marked differences in the results are observed when the sediment at different locations in the pipeline are scoured by water. Given that the flow shear stress decreases along with the scouring process, the sedimentation bed at the front section is greatly affected by scouring (Shahsavari et al. 2017).

Few studies on the migration of sediments (particulate matter) in drainage pipelines have calculated the sediment scouring rate and difference in sediment scouring across different locations of a pipeline. As mentioned earlier, the front section of a pipeline has a long sediment migration distance during the scouring–deposition alternating process. After scouring, the sediment at the front section may show patterns different from those at the middle and end sections. Therefore, the sediment scouring laws at the front, middle, and end sections of a pipeline should be reviewed, and a model for calculating the scouring rate should be established.

This study explores the scouring and transportation of sediments at different locations of a storm sewer, analyzes the influence of several factors such as sediment particle size, pipeline slope, sediment thickness, and water flow velocity, and builds mathematical models for quantifying the scouring rate of sediments at different locations of a pipeline. The results of this work can provide a foundation for further evaluating the pollution load on the receiving water body from sediments in storm sewer, for ensuring the continuous and stable operation of urban drainage systems, and for protecting the receiving water environment.

**MATERIALS AND METHODS**

**Test device**

A test device for simulating the sediment scouring and transportation process at different locations of a pipeline was built in a laboratory as shown in Figure 1. This device mainly comprised a water tank, test pipeline, flow meter, and valve. The pipeline has a total length and diameter of 12 m and 150 mm, respectively, and is manufactured with a Plexiglass tube. The top of the pipe was partially slotted by about a quarter of a circle to facilitate the placement of sediments in the tube. The valve and flow meter at the beginning of the pipeline were used to control the inlet water flow, and the height of the pipeline support can be adjusted to achieve different pipeline slopes.

The sediments used in the experiment were all taken from an actual outdoor storm sewer. Stones, branches, and other debris were removed in an indoor ventilated place, and the sediments were left to dry until reaching constant weight. A standard test was then performed to screen out sediment samples of different particle sizes for future use, and the density of the sediment was measured in a range of 2.34–2.51 g/cm³.

**Sampling and analysis methods**

To calculate the sediment scouring rate across different locations of the pipeline, the sediment samples were spread uniformly for about 0.5 m at the front (1.25 m–1.75 m), middle (6.25 m–6.75 m), and end (11.00 m–11.50 m) sections. When studying
the sediment scouring characteristics at the front section, only this section was evenly smeared with sediments. The same principle was followed for the middle and end sections. At the beginning of the test, the valve was opened to a certain flow, samples were taken from the outlet at the end of the pipeline across different time points, and the concentration of suspended solids (SS) was determined via the drying and weighing method (Bersinger et al. 2015).

During the experiment, change factors, such as sediment particle size, pipeline slope, sediment thickness, and water flow velocity, were recorded. The values of these factors were determined based on the actual pipeline situation and other documents (Table 1). The median particle size \(d_{50}\) of the sediment was 0.33 mm–0.83 mm, the pipeline slope \(i\) was 1.5‰–7.0‰, the sediment thickness \(h\) 0.20 cm–0.35 cm, and the water flow velocity \(v\) was 0.15 m/s–0.65 m/s. Before the experiment, the corresponding flow was determined for each flow velocity, the flow and flow velocity were measured with a flow meter and a portable flow velocity meter, separately. Each test was repeated for at least three times.

### Calculation model

According to the sampled sediment effluent SS concentration and flow rate, the flux in the pipeline \(B\) (the quality of the sediment passing through the pipeline per unit time), scouring volume \(W\) (the cumulative scouring volume of the pipeline at a certain moment), and scouring rate \(\varphi\) were computed as follows:

\[
B_i = \frac{C_i \times Q_i}{3,600} \quad (1)
\]

\[
W_i = \left(\frac{B_i + B_{i-1}}{2,000}\right) \times (t_i - t_{i-1}) + W_{i-1} \quad (2)
\]

\[
\varphi_i = \frac{W_i}{W_0} \times 100\% \quad (3)
\]

where \(C_i\) is the SS concentration of the effluent at time \(i\) (mg/L), \(Q_i\) is the flow rate at time \(i\) (L/h), \(B_i\) is the pipeline flux at time \(i\) (mg/s), \(W_i\) is the cumulative scouring amount of the pipeline at time \(i\) (g), \(\varphi_i\) is the scouring rate at time \(i\) (%), and \(W_0\) is the initial mass of the sediment (g).

### Table 1 | Test parameters and selection basis

<table>
<thead>
<tr>
<th>Test parameters</th>
<th>Used values in experiment</th>
<th>Reference values and source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow velocity (m/s) or flow (L/h)</td>
<td>0.15, 0.20, 0.30, 0.40, 0.62 m/s</td>
<td>720–1,440 L/h (Walski et al. 2009)</td>
</tr>
<tr>
<td>Median particle size (mm)</td>
<td>0.33, 0.59, 0.69, 0.83</td>
<td>0.006–2 (Xu 2013), 0.03–0.43 (Ebtchaj et al. 2016)</td>
</tr>
<tr>
<td>Pipeline slope (‰)</td>
<td>1.5, 3.0, 5.0, 7.0</td>
<td>1–3 (Bong et al. 2016), 3–7 (Jin et al. 2012)</td>
</tr>
<tr>
<td>Sediment thickness (mm)</td>
<td>0.20, 0.25, 0.30, 0.35</td>
<td>0–24 (Sang et al. 2017)</td>
</tr>
</tbody>
</table>
RESULTS AND DISCUSSION

Scouring flux and rate of sediment across different locations of a storm sewer

Figure 2 illustrates the calculation and analysis of scouring flux and scouring rate at different locations of the storm sewer under a certain sediment particle size, pipeline slope, sediment thickness, and water flow velocity.

Figure 2(a) shows that the flux decreases with time, especially in the first 30 s. At the initial stage of scouring (within 30 s), the flux of sediment at the front section of the pipeline was greater than that at the middle and end sections, whereas the flux at the middle and end sections of the pipeline was approximately 50% to 88% lower than that at the front section. After scouring for 30 s, the flux at the front, middle, and end sections of the pipeline did not greatly differ and were maintained within 100 mg/s. Previous studies show that the shearing force of the water flow gradually weakens along with the scouring of sediment from front to end (Campisano et al. 2008). Therefore, the sediment at the front section was relatively scoured away by the water flow, and the high concentration of suspended particles led to the greater flux at the front section of the pipeline than at the middle and end sections during the initial stage of scouring (Equation (1)).

An analysis of Figure 2(b) reveals that the scouring rates at the front, middle, and end sections of the pipeline increase with time and significantly increases in the first 60 s before slowly increasing. The scouring rate at the front section is higher than that at the other sections. When the water flows into the pipeline, the cross-sectional area of the water flow is small and concentrated. A strong impact force and high sediment scouring rate are also observed at the front section. As the water flows into the pipeline, the cross-sectional area tends to expand, and the water flow and shear forces are reduced in response to resistance (Campisano et al. 2007). In this case, the scouring capacity is reduced, thereby explaining why the scouring rates at the middle and end sections of the pipeline are significantly lower than that at the front section. During their scouring and transportation, the sediments are re-deposited (Mannina et al. 2012; Hannouche et al. 2014). After scouring and floating, part of the sediment at the end section of the pipeline was directly washed out of the pipeline, thereby explaining why the scouring rate at the end section was slightly higher than that at the middle section.

Factors that influence sediment scouring rate at different locations of a storm sewer

The sediment scouring process in a storm sewer is mainly affected by several factors, including sediment particle size, pipeline slope, sediment thickness, and water flow velocity. The sediment scouring rate at different locations in the pipeline after scouring by water for 5 minutes is affected by four factors as shown in Figure 3.

Figure 3(a) shows that when the particle size changes within a small range of 0.33 mm to 0.83 mm, an increase in particle size will gradually increase the sediment scouring rate at different locations of the pipeline. Part of the surface layer of the small particle size sediment can be easily peeled off, and the surface suspension layer formed via water scouring can be easily washed away by water. Therefore, at the early stage of scouring (e.g., within the first 30 s), the small particle size sediment showed a higher scouring rate. However, after scouring for some time, most of this sediment continued to adhere to the
bottom of the pipe in the form of agglomerates, had stronger adhesion to the pipe wall, and was relatively difficult to wash away compared with the larger particle size sediment (Black et al. 2002; Jiang 2012).

Figure 3(b) illustrates the influence of slope on scouring rate. The sediment scouring rates at the front, middle, and end sections of the pipeline increase along with the slope. A greater slope corresponds to a greater water flow, thereby facilitating the scouring and floating of the sediment. The most significant increase in scouring rate was observed at the later period. The initial kinetic energy was identified as a key factor that affects the magnitude of the shear stress generated by the water flow (Campisano et al. 2007). With a greater slope, the later part of the water flow potential energy is converted into kinetic energy, thereby increasing the water flow power and shear force. Therefore, the scouring rate in the later period significantly increases, and when the slope is large enough, the scouring rate at the end section may exceed that at the front section.

When the sediment thickness varies between 0.20 cm and 0.35 cm, the scouring rates at the front section ranged between 18.73% and 22.27%, which is slightly higher than that at the middle and end sections (Figure 3(c)). The scouring rates at the middle and end sections slightly increased along with thickness, which can be ascribed to the redeposit phenomenon during the transportation of sediment particles (Mannina et al. 2012; Hannouche et al. 2014). The more sediments are located at the end of the pipeline, the smaller the impact of redepositing. Therefore, the scouring rates at the middle and end sections slightly increase, whereas the scouring rate at the end section is higher than that at the middle section.

When the water flow velocity changes between 0.15 m/s and 0.65 m/s, the sediment scouring rates at the front, middle, and end sections of the pipeline all increase. However, when the water flow velocity is small (0.15–0.2 m/s), the difference among these scouring rates is small (Figure 3(d)). The front section receives the largest water flow shearing force, and as the flow...
velocity increases, the redeposit phenomenon during transportation becomes increasingly weak, thereby explaining why this section has the highest increase in scouring rate.

**Simulation of sediment scouring rate at different locations of a storm sewer**

At different positions of a storm sewer, the scouring rate under different scouring times was calculated by using Equations (1)–(3). Then via two data fitting, models for calculating the scouring rate across different locations of a storm sewer while taking different influencing factors into account were built.

**Simulation of scouring rate–sediment particle size**

The scouring rates of 1, 3, and 5 min were fitted under different sediment particle sizes. Results are shown in Figure 4.

The fitting results of the scouring rate with respect to the particle size in Figure 4, that is, the calculation models of the scouring rates of the sediments in the front, middle, and end sections under different scouring time are listed in Table 2.

According to Table 2, the general formula for calculating the scouring rate is preliminarily summarized as:

\[ \varphi = a \cdot X^b + c \]  

where \( \varphi \) is the scouring rate (%), \( a, b, \) and \( c \) are constants, and \( X \) is a parameter related to pipeline and sediment conditions (e.g., median particle size \([d_{50}]\), pipeline slope \([i]\), sediment thickness \([h]\), and water flow velocity \([v]\)). \( X \) in Table 2 represents particle size (mm).

![Figure 4](http://iwaponline.com/wst/article-pdf/84/6/1340/940105/wst084061340.pdf)

**Figure 4** | Fitting curve of scouring rate with respect to particle size under different scouring times \((v=0.3 \text{ m/s}, i=3.0\%\, \text{slope}, h=0.25 \text{ cm})\): (a) 1 min; (b) 3 min; (c) 5 min.
Two data fitting was applied on the fitting results for scouring rate shown in Table 2, and a functional relationship was established among constants $a$, $b$, and $c$ and flushing time. The calculation models (5), (6), and (7) for scouring rate under different sediment particle sizes and scouring time were eventually built as follows:

**Front section:**

$$\varphi = (-1.604 \times 10^{-16} t^{6.183} + 15.51)d^{0.000475 t^{1.337} + 1.441} + 0.1769 t^{0.7161} + 1.547$$  \hspace{1cm} (5)

**Middle section:**

$$\varphi = (1.402 d^{0.3636} - 4.283) t^{-1.835 \times 10^{19} t^{5.803} + 1.882} - 478.5 t^{-1.599} + 2.256$$  \hspace{1cm} (6)

**End section:**

$$\varphi = (2.063 \times 10^{16} t^{-8.351} + 13.04)d^{0.1807 t^{0.5742} + 1.811} - 4.738 \times 10^{6} t^{-2.862} + 1.571$$  \hspace{1cm} (7)

Using these equations, the sediment scouring rates across different locations of a pipeline can be calculated while considering a certain sediment particle size and scouring time.

**Simulation of scouring rate–pipeline slope**

Scouring rate with scouring times of 1, 3, and 5 min were fitted under different pipeline slopes. Results are shown in Figure 5. The fitting results for scouring rates under different slopes are shown in Table 3. Equation (4) was used for the calculation, with $X$ representing the slope, $900$.

After two data fitting, the calculation formulas of scouring rate under different pipeline slopes and scouring time were as follows:

**Front section:**

$$\varphi = (31.37 t^{0.2278} + 74.26) t^{246.3 t^{1.903} + 0.2105} - 32.54 t^{0.2283} + 86.41$$  \hspace{1cm} (8)

**Middle section:**

$$\varphi = (0.01531 t^{1.09} - 1.038) t^{(119.2 t^{1.197} + 0.6705)} - 0.05233 t^{1.027} + 4.073$$  \hspace{1cm} (9)

**End section:**

$$\varphi = (4.113 \times 10^{-8} t^{5.01} - 0.07747) t^{(-4.474 \times 10^{-5} t^{7.295} + 2.62)} - 5.571 \times 10^{-16} t^{6.183} + 3.978$$  \hspace{1cm} (10)
Using these formulas, the sediment scouring rates across different locations of a pipeline can be calculated at a certain pipeline slope and scouring time.

**Figure 5** | Fitting curve of scouring rate with respect to pipeline slope under different scouring times ($v = 0.3 \text{ m/s}$, $d_{50} = 0.83 \text{ mm}$, $h = 0.25 \text{ cm}$): (a) 1 min; (b) 3 min; (c) 5 min.

**Table 3** | Calculation of sediment scouring rates across different pipe slopes

<table>
<thead>
<tr>
<th>Time</th>
<th>Locations</th>
<th>Formula</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 min</td>
<td>Front section</td>
<td>$\varphi = 5.473i^{0.7347} + 3.559$</td>
<td>0.9981</td>
</tr>
<tr>
<td></td>
<td>Middle section</td>
<td>$\varphi = 0.2921i^{1.558} + 1.906$</td>
<td>0.9822</td>
</tr>
<tr>
<td></td>
<td>End section</td>
<td>$\varphi = 0.8672i^{2.567} + 3.362$</td>
<td>0.9930</td>
</tr>
<tr>
<td>3 min</td>
<td>Front section</td>
<td>$\varphi = 28.15i^{0.3111} - 20.06$</td>
<td>0.9970</td>
</tr>
<tr>
<td></td>
<td>Middle section</td>
<td>$\varphi = 3.68i^{0.9088} - 2.625$</td>
<td>0.9491</td>
</tr>
<tr>
<td></td>
<td>End section</td>
<td>$\varphi = 0.3299i^{2.266} + 4.573$</td>
<td>0.9990</td>
</tr>
<tr>
<td>5 min</td>
<td>Front section</td>
<td>$\varphi = 40.79i^{0.2572} - 33.23$</td>
<td>0.9955</td>
</tr>
<tr>
<td></td>
<td>Middle section</td>
<td>$\varphi = 6.652i^{0.7998} - 7.246$</td>
<td>0.9320</td>
</tr>
<tr>
<td></td>
<td>End section</td>
<td>$\varphi = 1.252i^{1.764} + 2.795$</td>
<td>0.9936</td>
</tr>
</tbody>
</table>
Simulation of scouring rate-sediment thickness

Scouring rates with scouring times of 1, 3, and 5 min were fitted under different sediment thicknesses. Results are shown in Figure 6.

The fitting results for the scouring rates under different sediment thicknesses are shown in Table 4. Equation (4) was used for the calculation, with \( X \) representing the thickness, cm.

After two data fitting, the calculation formulas of scouring rate under different sediment thickness and scouring time were as follows:

**Front section:**

\[
\varphi = (2.196 \times 10^{16}t^{-8.351} - 29.15) h^{(-1.613 \times 10^{15}t^{-8.345} + 1.109)} - 1.099 \times 10^{5}t^{-2.066} + 28.32
\]

**Middle section:**

\[
\varphi = (7515t^{0.1216} - 1.234 \times 10^{4}) h^{(-1.814 \times 10^{15}t^{-8.339} + 3.304)} - 4.561 \times 10^{14}t^{-8.266} + 3.257
\]
Using these formulas, the sediment scouring rates at different locations of a pipeline can be calculated at a certain sediment thickness and scouring time.

### Simulation of scouring rate–water flow velocity

Scouring rates with scouring times of 1, 3, and 5 min were fitted under different water flow velocities, and the results are shown in Figure 7.

The fitting results for scouring rates under different water flow velocities are shown in Table 5. Equation (4) was used for the calculation, with \( X \) representing velocity, m/s.

After two data fitting, the calculation formulas of scouring rate under different water flow velocities and scouring time were as follows:

#### Front section:

\[
\varphi = (-4.401 \times 10^{-12} t^{1.185} + 1.913 \times 10^4) h^{1.234} - 5.023 \times 10^{-18} h^{1.185} + 7.911) + 1.714 t^{0.3267} - 1.732
\]  

(13)

Using these formulas, the sediment scouring rates at different locations of a pipeline can be calculated at a certain water flow velocity and scouring time.

#### Middle section:

\[
\varphi = (-19.28 t^{3.358} - 32.38) v^{0.2782 t^{1.973} - 0.4948} + 43.66 t^{1.741} + 78.54
\]  

(14)

#### End section:

\[
\varphi = (3.965 t^{1.655} + 23.24) v^{0.9773 t^{0.497} + 1.55} - 2.451 t^{1.483} - 6.731
\]  

(15)

Using the above formulas, the sediment scouring rate across different locations of the pipeline can be calculated at a certain water flow velocity and scouring time.

### Comparison of the values calculated by the scouring rate model and the measured values

To verify the accuracy of the scouring rate model, its calculated values for sediment particle size were compared with the measured values. Figures 8 presents the comparison results.

Figures 8 compares the calculated values and measured values at a flushing time of 1 min. Across different particle sizes, the difference between these two sets of values is relatively small (–0.63% to 0.63%, –0.01% to 0.02%, and –0.13% to 0.16% for the front, middle, and end sections, respectively). In sum, the model calculations are consistent with the actual measured values, thereby validating the high accuracy of the model.
Figure 7 | Fitting curve of scouring rate with respect to water flow velocity under different scouring times ($d_{50} = 0.83$ mm, $i = 3.0\%$, $h = 0.25$ cm): (a) 1 min; (b) 3 min; (c) 5 min.

Table 5 | Calculation of sediment scouring rate across different water flow velocities

<table>
<thead>
<tr>
<th>Time</th>
<th>Locations</th>
<th>Formula</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 min</td>
<td>Front section</td>
<td>$\varphi = -81.66v^{-0.2166} + 122.2$</td>
<td>0.9829</td>
</tr>
<tr>
<td></td>
<td>Middle section</td>
<td>$\varphi = 27.21v^{0.5722} - 9.182$</td>
<td>0.9501</td>
</tr>
<tr>
<td></td>
<td>End section</td>
<td>$\varphi = -33.67v^{-0.1784} + 48.09$</td>
<td>0.8944</td>
</tr>
<tr>
<td>3 min</td>
<td>Front section</td>
<td>$\varphi = -33.61v^{-0.4454} + 77.58$</td>
<td>0.9860</td>
</tr>
<tr>
<td></td>
<td>Middle section</td>
<td>$\varphi = 47.68v^{0.336} - 25.30$</td>
<td>0.9482</td>
</tr>
<tr>
<td></td>
<td>End section</td>
<td>$\varphi = -14.10v^{-0.4249} + 32.87$</td>
<td>0.9379</td>
</tr>
<tr>
<td>5 min</td>
<td>Front section</td>
<td>$\varphi = -32.60v^{-0.4727} + 79.51$</td>
<td>0.9869</td>
</tr>
<tr>
<td></td>
<td>Middle section</td>
<td>$\varphi = 80.16v^{0.2075} - 54.34$</td>
<td>0.9340</td>
</tr>
<tr>
<td></td>
<td>End section</td>
<td>$\varphi = -23.28v^{-0.3474} + 46.43$</td>
<td>0.9561</td>
</tr>
</tbody>
</table>
CONCLUSION

(1) The proposed model can be used to calculate the sediment scouring flux and rate across different locations of a storm sewer. The scouring rate is affected by sediment particle size, pipeline slope, sediment thickness, and water flow velocity. As the slope increases, the scouring rate at the end section of the pipeline shows the most obvious increase. Meanwhile, the scouring rate at the front section slightly decreases along with increasing sediment thickness, whereas the opposite is observed at the middle and end sections. When the sediment particle size (0.33 mm–0.83 mm) and flow velocity (0.15 m/s–0.65 m/s) increase within their ranges, the sediment scouring rate increases across the three sections of the pipeline.

(2) Models for calculating scouring rate under the influence of sediment particle size, pipeline slope, sediment thickness, and water flow velocity were established. For example, by using Equations (5) to (7) for ‘scouring rate–sediment particle size’ the sediment scouring rate at different locations in a pipeline can be calculated at a certain sediment particle size and scouring time.

(3) The calculated values were compared with the measured values at a scouring time of 1 min. Under different particle sizes, the difference between the calculated and measured values at the front, middle, and end sections were in the ranges of −0.63% to 0.63%, −0.01% to 0.02%, and −0.13% to 0.16%, respectively. These values showed good consistency, and the differences were relatively small. The models showed a good accuracy.
Overall, these mathematical models can calculate the scouring rates of sediments at different locations of a pipeline under a certain condition. It is helpful for further evaluating the contribution of sediment scouring in pipelines to downstream pollution. However, in subsequent research, the models will be updated to cover more factors, so the scope of their application will be broadened.

ACKNOWLEDGEMENT

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES


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