Research Article

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An experimental and numerical study investigating sediment transport position in the bed of sewer pipes in Karbala

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Abstract: The complex phenomenon of sedimentation in urban areas is well studied using numerical models. Because they may be used to mimic sediment flow, obstructions, and drainage system optimization, the simulations are useful in urban planning and design. By merging ANSYS Fluent with Rocky, researchers were able to track the motion of sediment particles of various sizes and speeds. The sizes of the sediment particles were measured using a sieve after being collected from the streets of Karbala. The particle sizes established by the sieve analysis were used in both the computational and experimental procedures. Varied particle sizes and velocities, including 0.1, 0.2, 0.3, 0.35, 0.4, and 0.49 m/s, as well as varied particle sizes, including 0.4, 0.6, 0.8, 0.1, and 1.2 mm, were investigated. Numerical analysis showed that 1.2 mm-sized particles sedimented between 10 and 148 cm from the input pipe's *X* coordinate at a rate of 0.49 m/s. A maximum sedimentation distance of 380 cm was also observed for particles with a diameter of 1 mm. Sediment did not include 0.4 mm-sized objects flowing at the same speed. The findings demonstrated that particle size and velocity significantly impacted the quantity of drag and lift forces acting on the particles. As the particle size increased, the drag force increased, which led to more sedimentation. The particle positions along the *X* coordinate (pipe bed) showed a declining trend. Overall, this work offers crucial insights for understanding sediment transport in urban drainage systems by illuminating the connection between velocity, particle size, and sedimentation behaviour.

Keywords: sedimentation, velocity of water, sewer pipe

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1 Introduction

In recent years, state-of-the-art numerical simulations have become increasingly popular for addressing complex water management challenges in urban areas. These simulations have proven helpful in modelling sediment transport and blockages, optimizing drainage systems, and facilitating planning and design [1]. Modelling is an effective solution for tackling such complex issues. Results from these simulations have indicated that the pipes' lateral displacement strongly depends on the pipe's depth ratio (X/H). Increasing the depth ratio leads to a decrease in pipe displacement.

Additionally, the results have shown that a higher modulus of backfill soil results in a more remarkable soil restraint on the pipe, resulting in negligible lateral movements. Moreover, increasing pipe diameter and footing pressure increases pipe displacements. Displacement charts were developed based on finite element results [1].

Typically, hydraulic modelling focuses on non-pressurized systems such as open channels and gravitational streams. These systems are primarily affected by heavy rainfall events, combined sewer flows, and pollutant loads. As a result, scientific research has mainly focused on gravitational streams. Although compact systems are included in urban drainage modelling programs, they are less critical in engineering sciences. This is because the primary issues affecting water management in urban areas are related to gravity ducts, such as overloading, flooding, combined sewer overflow, and fat deposition. The discharge capacity of urban drainage systems is evaluated and simulated through a numerical analysis model that considers the flow pattern of sediments in sewage conduits. During the sedimentation process, septic system discharges caused by sedimentation in sewers are also evaluated, resulting in a plan to design urban drainage systems with increased water-draining capacity [2].

The Storm Water Management Model program was used to simulate the stormwater network in Basra and predict annual precipitation in the future until 2099 using the Statistical Downscaling Model. The results indicate a future increase in temperature of 0.14–1.07°C as a maximum. Due to climate change, the rain intensity is expected to exceed the network capacity, reaching 21.5 mm/h, while the network's design capacity is 11.5 mm/h. Consequently, 34% of manholes are expected to overflow [3].

Sediment transport in sewer systems can be modelled using two types of models: morphological and mathematical. Morphological models, also known as detailed sediment transport models, use the physical characteristics of the particles being transported, which are often simplified. The Eulerian approach is a commonly used granular-fluid modelling technique that considers fluid and solid phases as interpenetrating continuums within a computational cell. The sensitivity analysis results show that the index of flow depth/width ratio (y/b) significantly influences local scour depth predictions compared to other input variables [4]. Constitutive equations are required for inter- and interphase interactions. The main advantage of the Eulerian approach is its reasonable computational cost [5]. However, obtaining general equations for granular systems is challenging due to the changing nature of how solids flow. The accuracy of the continuous approach in generating precise results relies heavily on the constitutive relations utilized to model the interactions between the phases and the rheology of the particulate material, which can be pretty challenging to obtain [6]. During the self-weighted consolidation settlement stage, sediment settles faster than the adequate particle pressure dissipates, causing settling between 32 and 59% of the original depositional height [7].

Urban drainage systems play a critical role in efficient sewage management and the economic performance of cities [8]. However, sediment deposition is a significant problem that affects the design and operation of sewerage systems [8]. To investigate the hydraulic characteristics of sediment transport in circular channels with different bed slopes, a 3D numerical simulation of the flow field was conducted using ANSYS-CFX software. Similarly, Hussein et al. [9] aimed to determine the significant differences in biological oxygen demand and total suspended solids parameters during rainy seasons using SWMM5. Their study highlights the importance of understanding the impact of rainfall on wastewater quality in sewer networks.

Sediment-laden pipe flows with larger particle sizes and suspended loads result in undamped flow turbulence and more excellent flow resistance [10]. Alihosseini and Thamsen [11] developed and validated a computational fluid dynamics (CFD) model that accurately predicts turbulence in circular pipes, showing that bed roughness affects the velocity and shear stress distributions in partially filled pipes. Nayel et al. [12] investigated the impact of an 80-percentile rainfall event on sewer overflow and surface in Iraq, aiming to assist in designing and managing urban sewerage systems.

Sediment transport in pipes is crucial for redistributing water and serves as a sediment resource for various projects [13]. Numerical models are increasingly used to simulate flow, sediment transport, and morphological changes in rivers, but the applicability of commonly used empirical sediment transport models is often limited [13]. Montes et al. [14] used numerical and experimental methods to investigate sediment movement in sewage pipes and determine whether CFD-DEM-linked techniques accurately predict sediment behaviour in sewers. Mohammed et al. [15] proposed a dimensionless model to estimate the erosion rate caused by soil erosion in urban areas due to water movement through defects in sewer pipes.

The discharge capacity of urban drainage systems is assessed and simulated through a numerical analysis model that considers sediment flow patterns in sewage conduits [7]. Similarly, Rinas et al. [16] developed and calibrated a sediment transport model using in situ data to examine sediment movement in a pressure pipe. Mohammed et al. [15] used a numerical simulation with FLOW-3D to predict and discuss turbulent energy dissipation in stilling basins, which can help hydraulic designers make more informed decisions in selecting the optimal design of stilling basins.

A pilot plant test facility and CFD simulations were used as the first steps in this research to develop a comprehensive experimental dataset and assess the transport properties of sand-water mixes.

2 Materials and mythology

2.1 Study area, components of laboratory experimental device, and equation

A pump equipped with a large 2000-l water tank was used in the Karbala plant field to carefully monitor the transport of sand grain sizes while operating at a controlled speed to ensure accurate control. An 8-in. tube that connects to the water tank at the top allows for easier water movement and has a sediment feeder at its beginning.

Transmission controls are used to turn on and off the pump at a predetermined flow rate as sediment is fed through the unit's supplied sand particles. As shown in Figure 1, during the opening 15 min, silt of varied sizes was continuously added to the flow. To identify the particle size that affects sedimentation, the particle size was collected from the streets of Karbala and subjected to sieve

Figure 1: The sand collection and sieve analysis.

examination. The migration of the sediment to the pipe bed for each interval was also tracked and recorded as it passed through the openings at the back of the pipe. A representative section of the system used in the real-world experiment is shown in Figure 2.

Gravel settling in sewer systems can result in obstructions, which can have a negative impact on the environment and human health. The goal of this experiment is to quantify the volume of gravel that has accumulated in various locations inside a plastic UPVC pipe with an 8-in. diameter and a slope of 0.44 cm every 6 m of pipe length. We investigated the impact of three variables on gravel settling: velocity, particle size, and sedimentation rate relative to water flow rate. We calculated the flow and discharge velocity using the Manning equation.

$$Q = \frac{1}{n} \times A \times (R)^{0.66} \times S^{0.5}, \tag{1}$$

n stands for the Manning roughness coefficient, Q stands for the pipe flow rate in metres per second (m^3/s), A stands for the flow's cross-sectional area normal to the flow's direction (m^2), S stands for the pipe's degree of downhill slope (in metres per metre), and R stands for the hydraulic radius (Rh). The ratio of the flow's cross-sectional area to its wetted perimeter, represented by P, is used to compute the Rh. By calculating the discharge of the flow in the pipe using the Manning equation, we were able to apply that equation to get the flow velocity.

$$V = \frac{1}{n} \times (R)^{0.66} S^{0.5}. \tag{2}$$

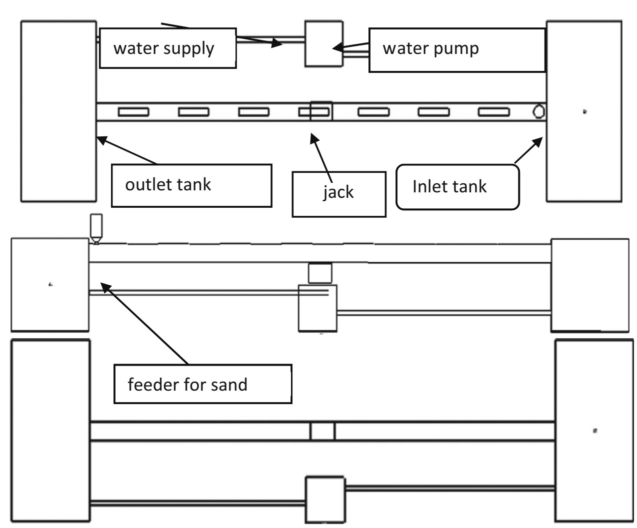


Figure 2: The laboratory device that was used to simulate the sediment in the pipe sewer.

Two scenarios of flow inside the pipe are shown by the Manning equation. As seen in Figure 3, the hydraulic diameter is greater than half of the discharge in the second case whereas it is less than the flow in the first. In both instances, we ran tests to see how different flow rates, particle sizes, and sedimentation rates in relation to water flow rates affected the amount of gravel that settled in the sewage line. The numerical results from the ANSYS Fluent and Rocky software were based on laminar flow conditions.

2.2 Numerical method

The software packages ANSYS and Rocky were used to analyse the numerical data. One of the phenomena that can be depicted with the use of ANSYS and Rocky is sedimentation in sewage lines. It was simpler to picture the movement and settling of water and silt in sewer pipes because the simulation employed the same concepts as tests. Evaluation of the degree of complementarity between the two programs is also essential.

Obtaining generic equations for granular systems is difficult since a solid's flow characteristics are always changing. Although the constitutive relations used to simulate the interactions between the phases and the rheology of the particulate material can be fairly difficult to establish, they are crucial to the continuous approach's accuracy in producing exact findings [6].

Excluding intrusion, it is worth noting that the continuum interpenetrating approach used in this study does not provide information about individual particles. This may be a limitation for those seeking particle-specific data. Additionally, prescribing a particle size distribution can significantly increase computational costs, as multiple phases must generally be modelled to account for different particle sizes.

The combination of discrete particle methods and a finite volume method for solving the fluid phase at the cell level, known as the DEM-CFD approach, offers a promising alternative for modelling granular-fluid systems. By resolving fluid flow at the cell level rather than the particle level, this approach can account for the discrete nature of the particle phase while still maintaining computational

(a)

$$r = \frac{D}{2} \quad (3)$$

$$\Phi = 2COS^{-1}\left(\frac{r-h}{r}\right) \quad (4)$$

$$A = \frac{r^2(\Phi - sin(\Phi))}{2} \quad (5)$$

$$p = A\Phi \quad (6)$$

$$R = \frac{A}{P} \quad (7)$$

(b)

$$\Phi = 2COS^{-1}\left(\frac{r-h}{r}\right)$$

$$A = r^2\pi - \frac{r^2(\Phi - \sin(\Phi))}{2} \quad (8)$$

$$p = 2\pi r - r\Phi \quad (9)$$

$$R = \frac{A}{P}$$

Figure 3: The hydraulic radius in the pipe. (a) The hydraulic radius is less than the flow; (b) the hydraulic radius is higher than half of the flow.

tractability. This allows for a broader range of equipment and processes to be studied through numerical simulations. The coupling of DEM with a finite volume method was initially described by Guanabara [17] and Hoomans et al. [18]. Various authors have utilized the soft-sphere and hard-sphere models to conduct their research, such as Hoomans et al. [19], Xu et al. [20], and Collinson et al. [21].

2.2.1 Particle *X*-coordinate

The three pipe coordinates (*X*, *Y*, and *Z*) are shown in Figure 4. The *X*-coordinate denotes the length of the pipe, the *Y* coordinate denotes the depth of the pipe's water, and the *Z* coordinate denotes the width of the water flow. Figure 4 displays the particle for the *X*, *Y*, and *Z* coordinates. These coordinates in relation to the run time will serve as a representation of the particle position in the pipe. The correlation between water velocity and particle size is depicted in Figure 4.

2.2.2 Particle sediment position

This study used the Fluent and Rocky software to forecast the precise placement of silt particles inside a pipe

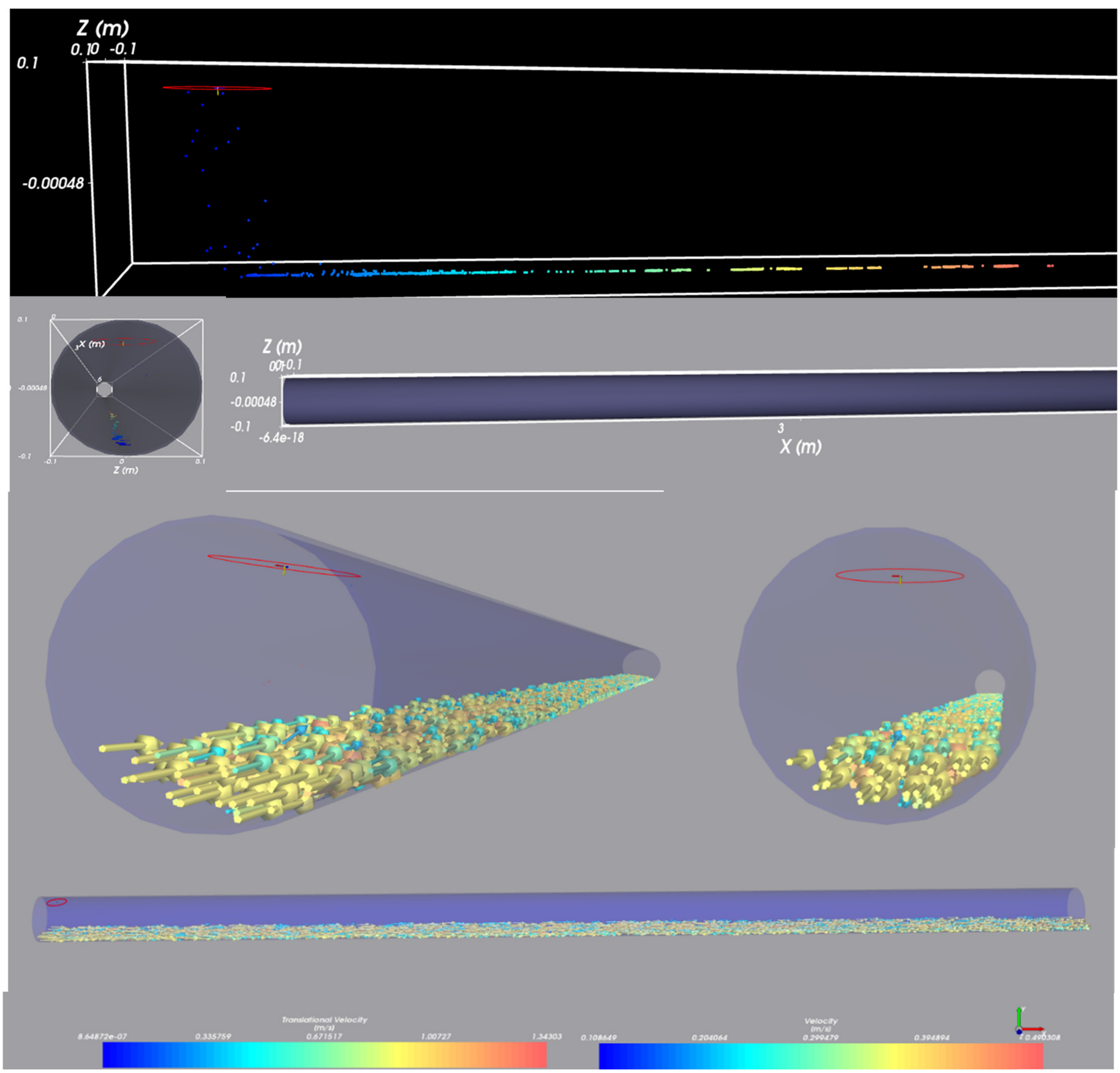


Figure 4: Particle and water velocities with ANSYS Fluent and Rocky after coupling them.

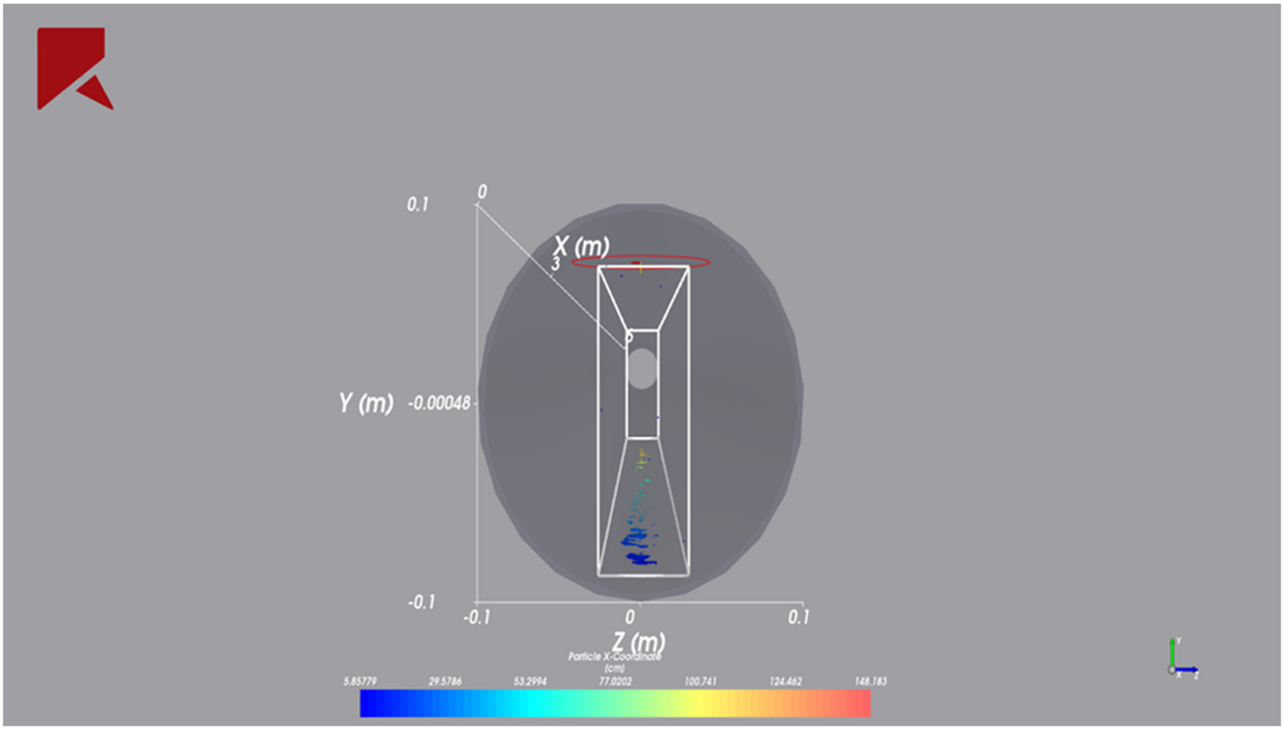


Figure 5: Particle location along the *X*-axis in a pipe under water flow.

transporting water flow. In addition to using extra axis information to pinpoint the particle's precise location within the pipe along the *Y*- and *Z*-coordinates, the *X*-coordinate was used to show the particle's position along the length of the pipe regarding the analysis time. The position of particles along the *X*-coordinate is graphically shown in Figure 5, with various colours denoting their velocities. The investigation discovered that while some blue particles were in motion, others had settled and gathered in particular places.

3 Results

3.1 Experiential result

The expert interpretation of the experimental data on sedimentation inside an 8-in. pipe is presented in this section. The results provide insight into how different materials behave under controlled circumstances, with an emphasis on the variables that impacted the sedimentation process.

The outcome demonstrates the connection between sediment particle properties and their settling path through a sewer system. The exact distance along the sewer at which particles with a certain dimension and velocity will deposit due to gravity and other forces is represented by the *X*-coordinate, which is examined. The particle can move farther before settling the higher the *X*-coordinate value.

According to the study, the maximal *X*-coordinate of sediment particles increases as their diameter decreases. This trend is explained by the fact that smaller particles are less likely to settle and are therefore more easily carried by fluid flow. Additionally, as illustrated in Figure 6, a drop-in velocity results in weaker fluid forces that are less efficient at transporting and suspending sediment particles, which reduces the maximum *X*-coordinate. The figure shows the beginning spreading of 1.2 mm-sized particles 150 cm from the sediment feeder on the tube's bottom. On the other hand, at the bottom of the pipe, 1 mm-sized particles dispersed over a distance of 320 cm. Along the line, sediments of diameters 0.8, 0.6, and 0.4 mm were likewise applied; however, their concentrations varied and fell off as the diameter increased. The sediment position in the tube bed for various sizes is described in Table 1.

3.2 Numerical result

According to the information given, the sediment particles inside the pipe seem to be scattered unevenly and come in a variety of sizes. As shown in Figure 7, the sediment

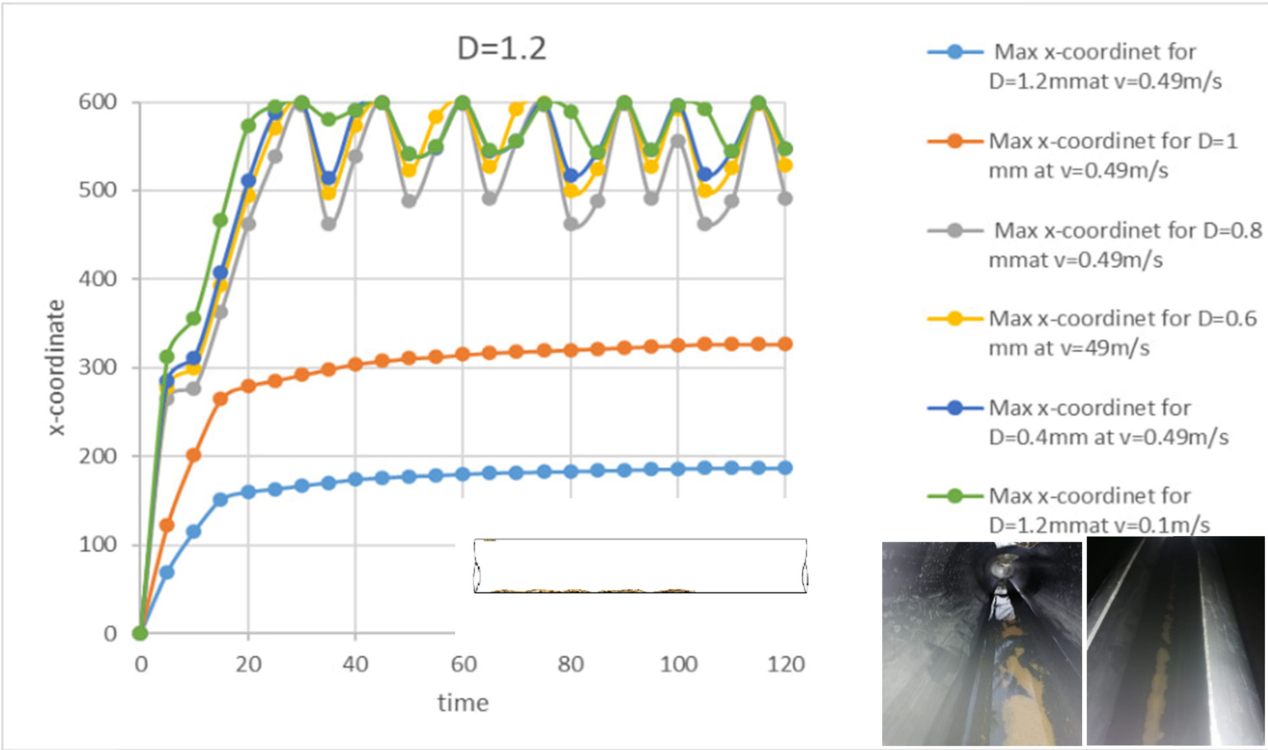
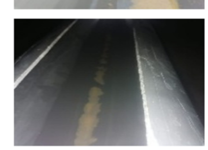
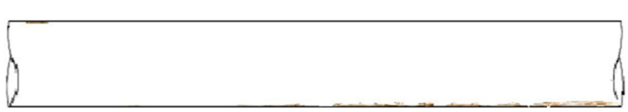


Figure 6: Sediment particle settling distance: relationship with diameter and velocity.

Table 1: Position sediment transport in pipes

Particle diameter in (mm)	Sediment distribution on the bed of the pipe	
D = 1.2 mm		
D = 1 mm		
D = 0.8 mm		
D = 0.6 mm		
D = 0.4 mm		

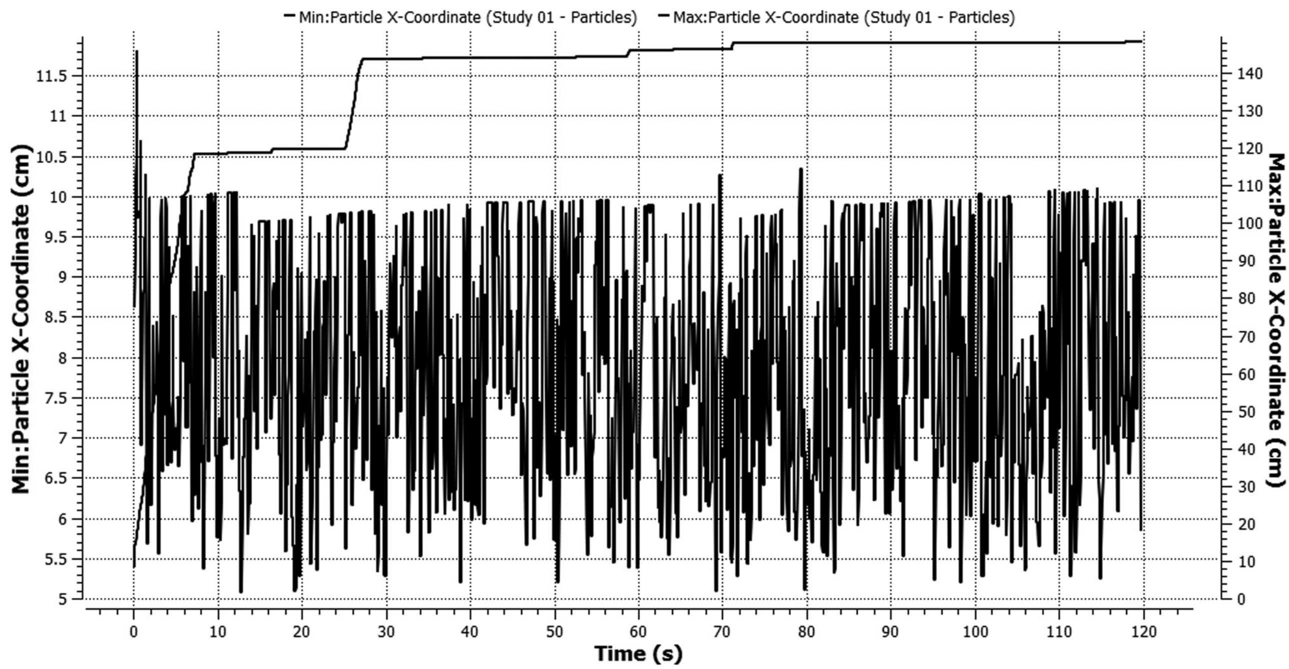


Figure 7: Maximum and minimum particle *X*-coordinate.

particles are seen to collect specifically within the range of 0–148.1 cm along the *X*-coordinate from the inlet side, with a breadth range of 0–3 cm.

Table 2 demonstrates that when a cross-sectional view of the pipe is obtained, a constant water velocity of 0.49 m/s causes a variation in the sediment particle distribution along the length of the pipe. The range of particle diameters measured shows this phenomenon to be widespread. These sediment particles appear to have an effect on the overall rate of sedimentation inside the pipe, possibly obstructing the flow of other particles and causing more sediment to accumulate. These results imply that the presence and size of sediment particles inside a pipe can have significant effects on the system's overall flow dynamics and sediment build-up.

3.2.1 Effect of different velocities on the particle diameter along the maximum *X*-coordinate sedimentation

This study looks into the connection between water flow rate, velocity, and particle behaviour during sedimentation. As seen in Figures 8 and 9, we specifically study the behaviour of particles with diameters of 1.2 and 1 mm moving at various speeds (0.49, 0.4, 0.35, 0.3, 0.2, and 0.1 m/s). The findings show that the volume and location of the sedimented particles are directly influenced by the water's velocity. The figures also show that, as seen by the various *X*-coordinates of the settled particle, the diameter of the particles also influences their diffusion on the base of the pipe.

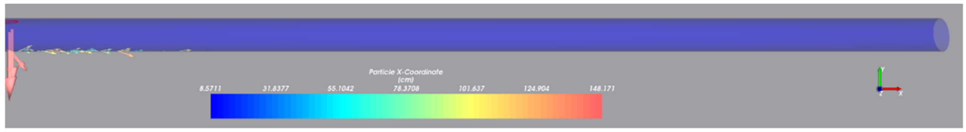
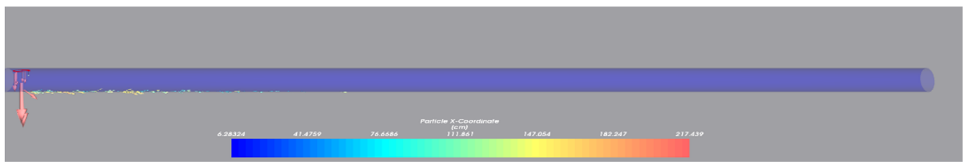
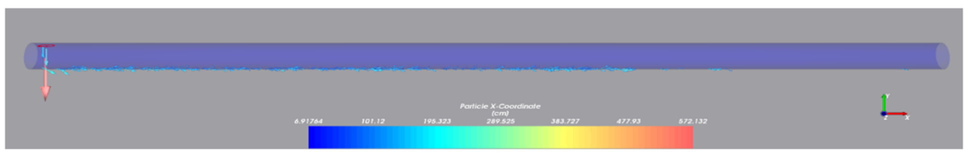
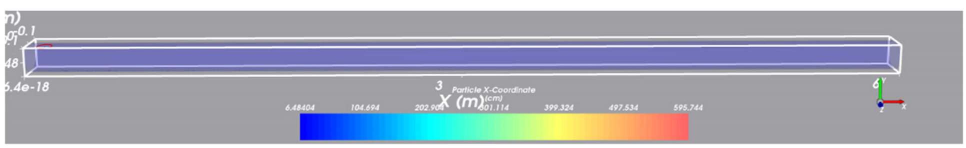
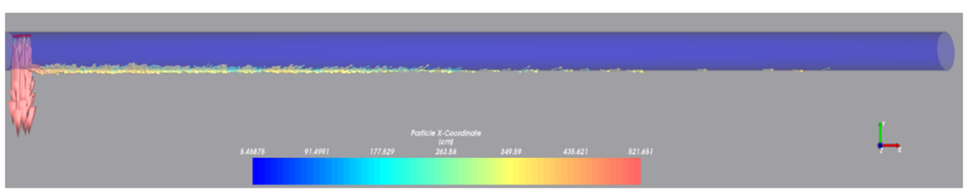
Figures 9 and 10 show the sedimentation outcomes for particles of various sizes and velocities in a pipe. Particles having a diameter of 1.2 mm can reach a maximum position of 148 cm at a sedimentation velocity of 0.49 m/s and 90 cm at a velocity of 0.1 m/s, which declines as sedimentation velocity increases.

The maximum position also declines for particles with a diameter of 1 mm, going from 391 cm at a velocity of 0.49 m/s to 238 cm at a velocity of 0.1 m/s. It is important to keep in mind that, at a certain sedimentation velocity, the maximum position also decreases as the particle diameter increases.

These findings are in line with the rules of sedimentation, which suggest that at a given sedimentation velocity, smaller particles take longer to settle than bigger particles. Additionally, as the sedimentation velocity declines, the settling time lengthens, which causes particles to reach lower maximum locations.

The impact was assessed using Figure 10 while keeping a constant velocity between 0.49 and 0.1 m/s. The outcomes show that, in comparison to the earlier diameters, the influence of particle diameter was more pronounced. Particularly, the sediment reached the pipe's furthest point in the *x* direction and showed particle escape outside the

Table 2: The particles position at different diameters and 0.49 m/s velocity

Particle diameters (mm)	Velocity 0.49 m/s
D = 1.2 mm X_{max} = 148 cm	
D = 1 mm X_{max} = 380 cm	
D = 0.8 mm X_{max} = 599 cm	
D = 0.6 mm X_{max} = 599 cm	
D = 0.4 mm X_{max} = 599 cm	

pipe's outer perimeter (outlet). As shown in Figures 11 and 12, this phenomenon was more pronounced with lower diameters 0.6 and 0.4.

Velocity and diameter have a big influence on how particle sedimentation behaves, as seen in Figure 13. The outcomes show that at a velocity of 0.49 m/s, particles settle more quickly and go to a place with a smaller maximum X-coordinate. On the other hand, the maximal X-coordinate location increases at the same velocity as the particle diameter decreases. One example is that 1.2 mm diameter particles settled at a minimum X-coordinate position of 150 cm along the pipe. Particles having a diameter of 0.4 mm, in contrast, completely left the pipe. Additionally, if the velocity is maintained while the particle size is reduced, the distance across which the sediment is distributed at the bottom of the pipe grows, increasing the X-coordinate. The X-coordinate has reached its maximum position, and the particle size of 0.4 mm shows that all of the sediment has exited the pipe.

4 Discussion

The results presented in the given information show that the sediment particle size significantly impacts the sedimentation process within a pipe. Specifically, as the size of sediment particles decreases, the maximum distance that the particle can travel before settling, represented by the X-coordinate, increases. This is due to smaller particles being more easily transported by fluid flow and experiencing less settling. Conversely, larger particles

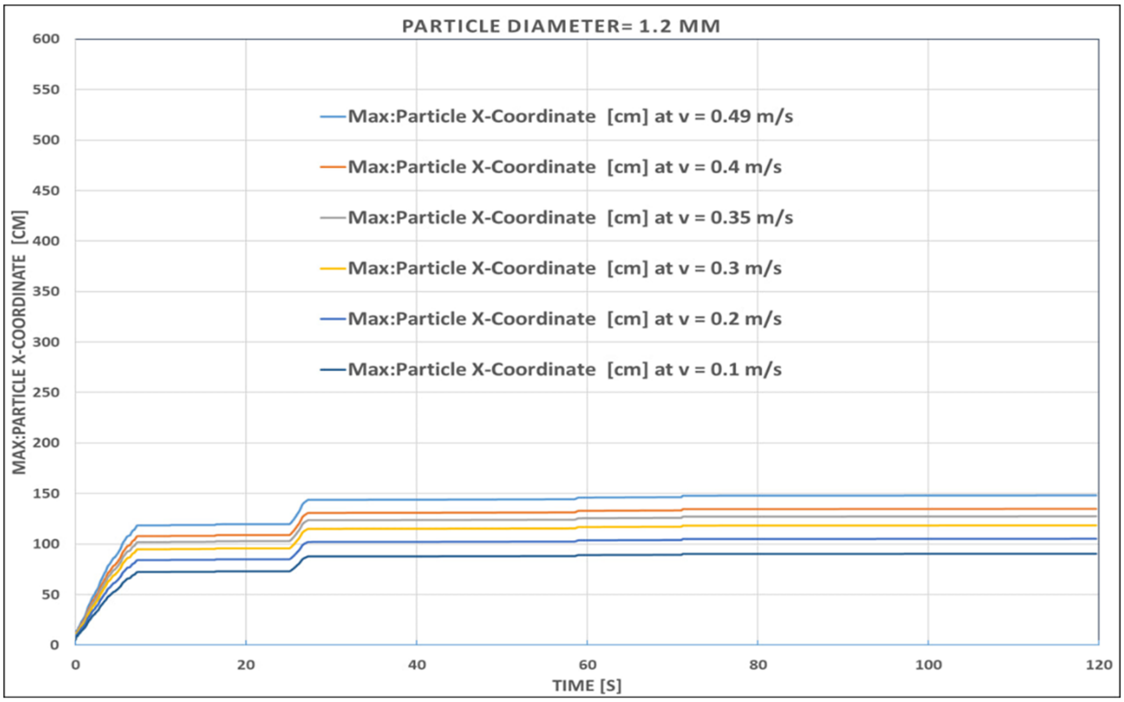


Figure 8: The particle with a 1.2 mm position along the pipe's axis with respect to different velocities.

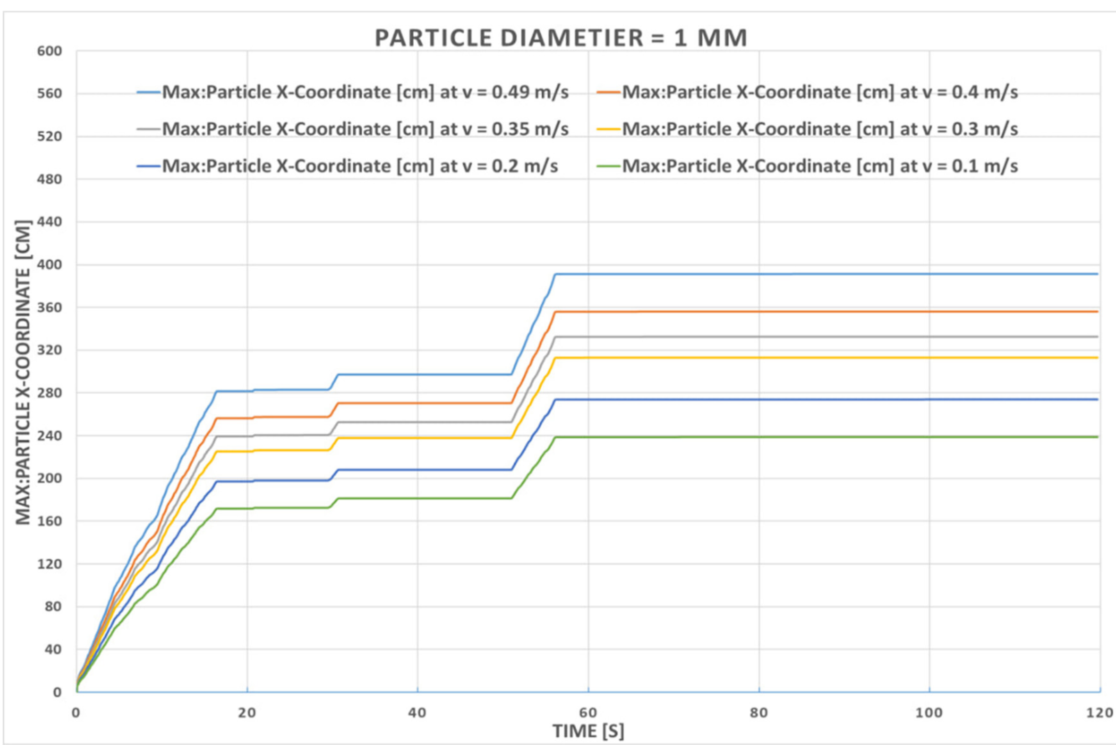


Figure 9: The particle 1 mm position along the *X*-coordinate of the pipe at a velocity.

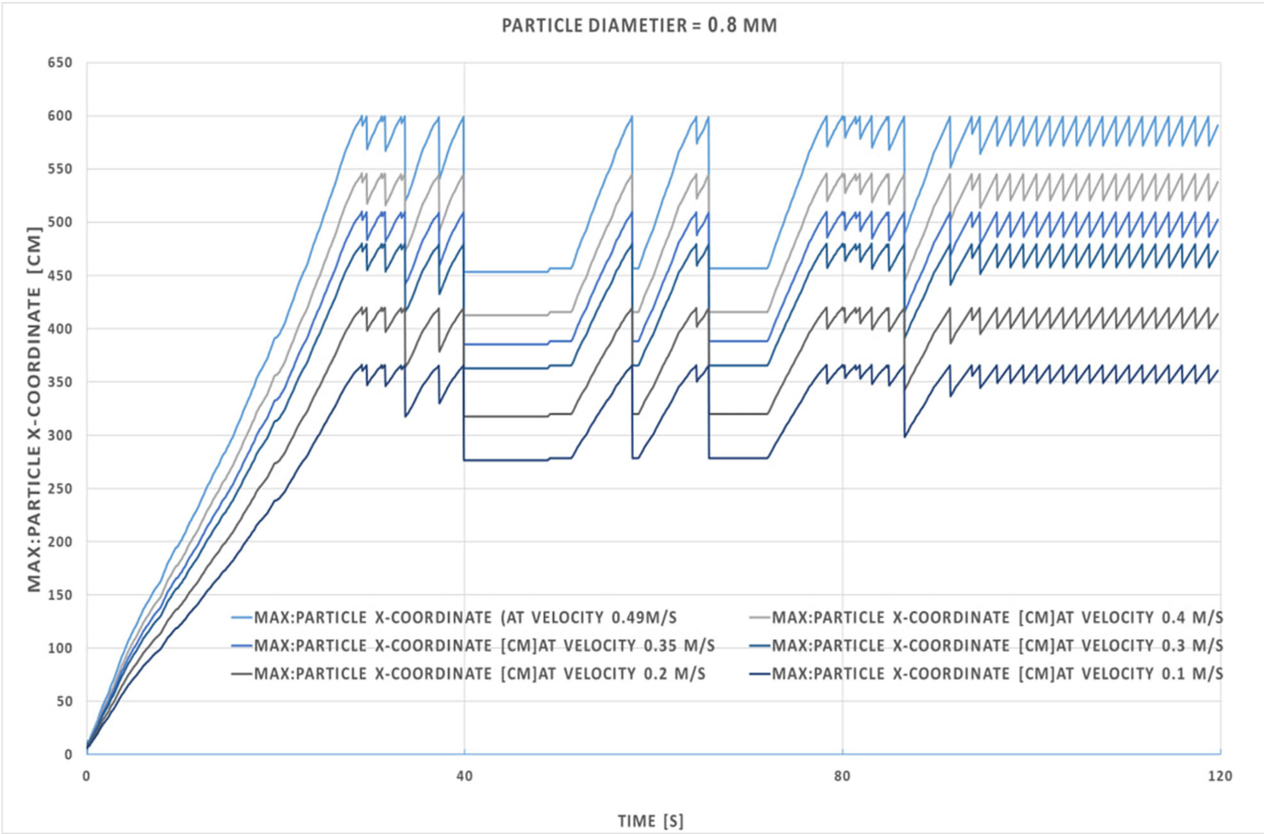


Figure 10: The particle's 0.8 mm position along the axis of the pipe with respect to different velocities.

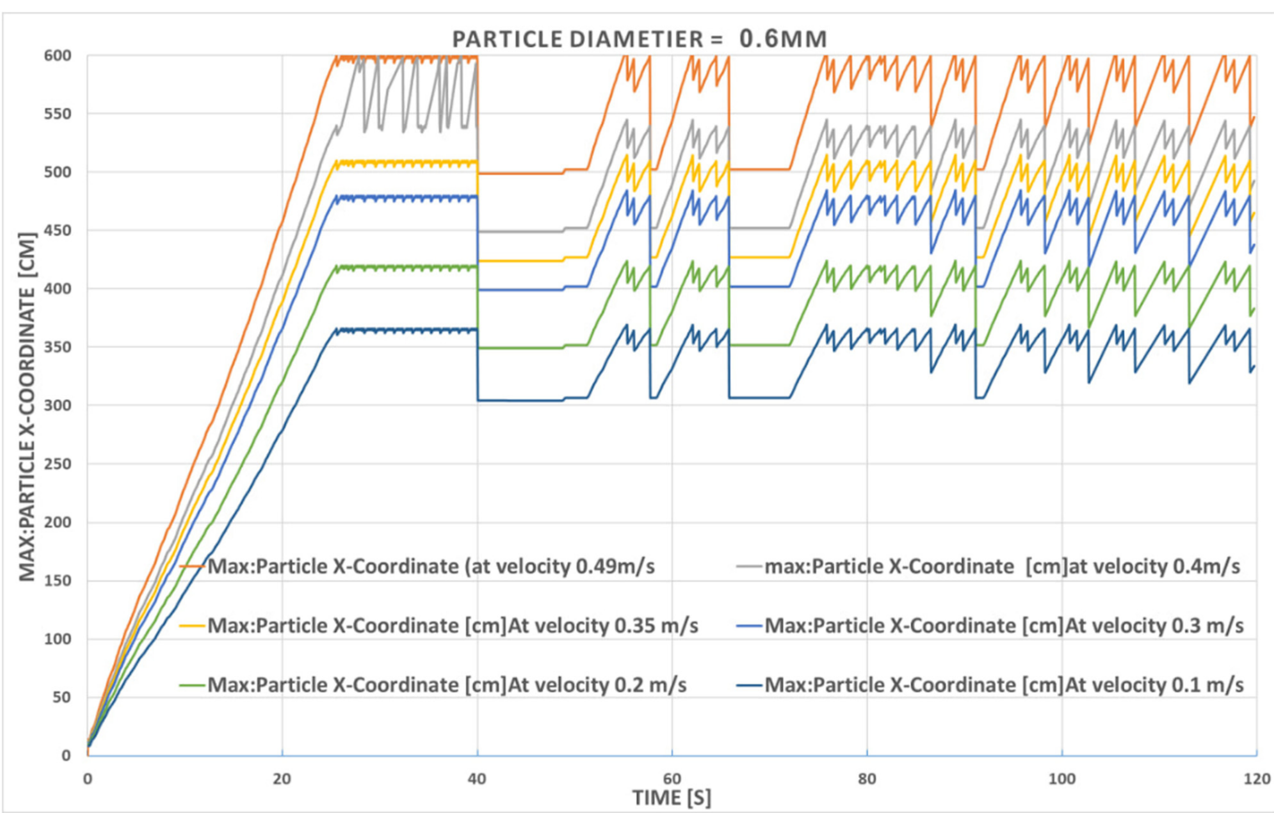


Figure 11: The particle's 0.6 mm position along the *X*-coordinate of the pipe with respect to the velocities.

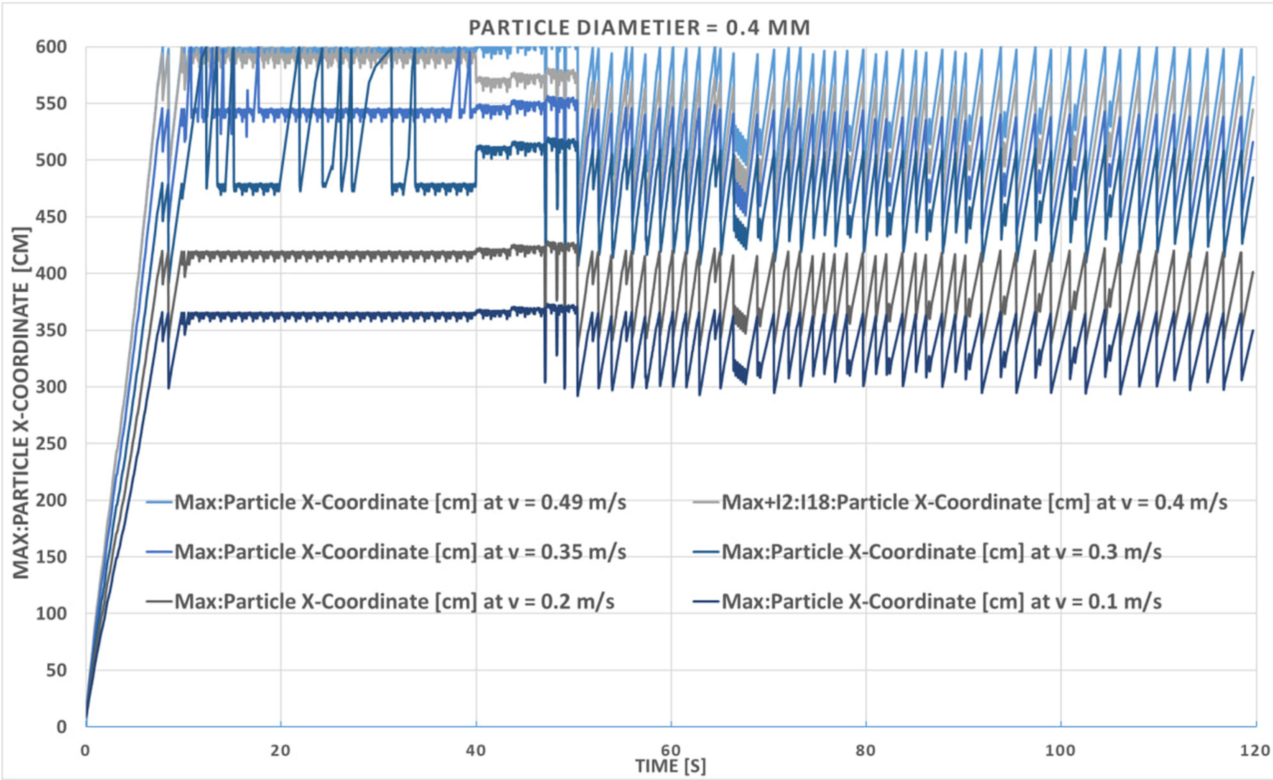


Figure 12: The particle's 0.4 mm position along the axis of the pipe with respect to different velocities.

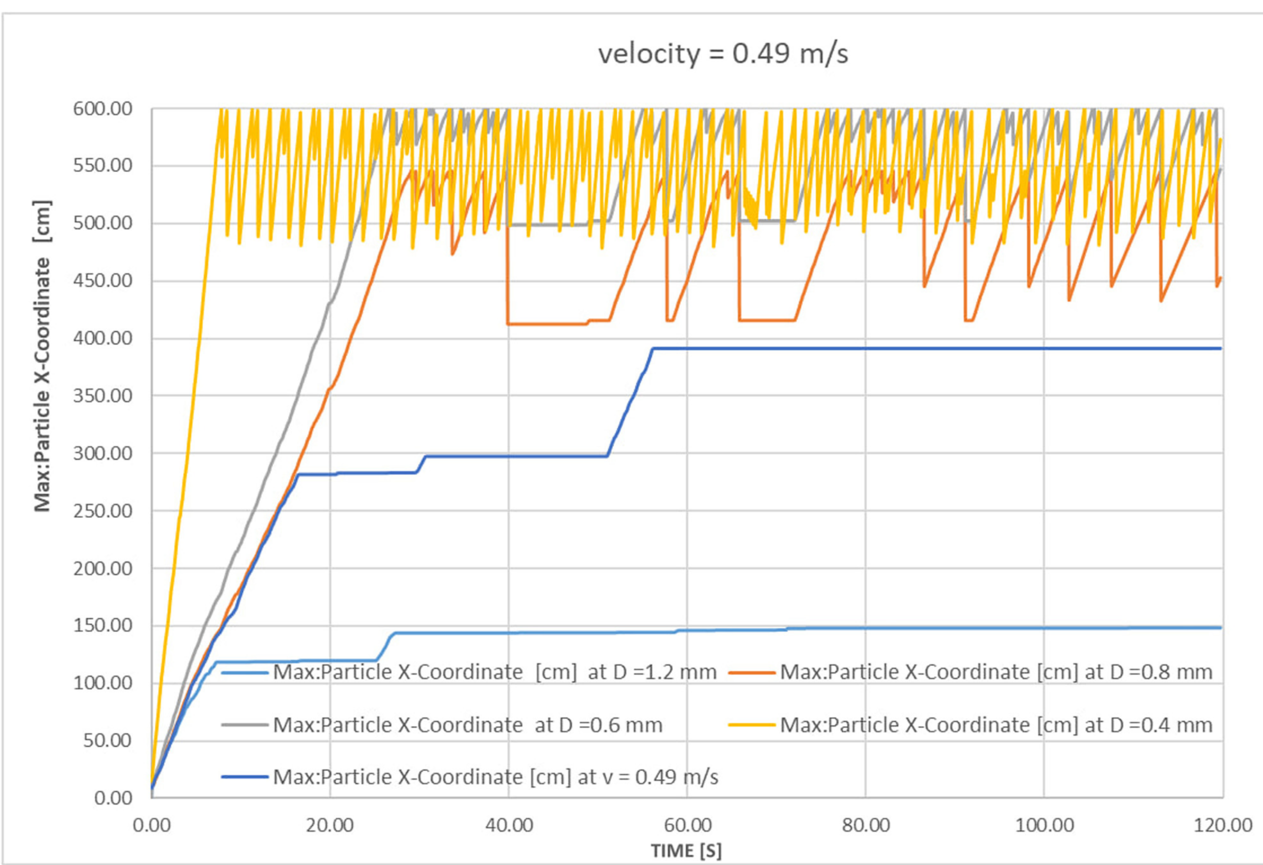


Figure 13: Maximum *X*-coordinate positions of sediment in particles at different particles at velocity 0.49 m/s.

experience more vital settling forces and are more likely to deposit closer to the inlet side of the pipe. In addition, the velocity of the water flow significantly affects the sedimentation process. A decrease in velocity reduces the maximum *X*-coordinate, as lower velocities lead to weaker fluid forces that are less effective in transporting and suspending sediment particles. This suggests that higher water velocities may be more effective in preventing sediment build-up and promoting sediment transport within a pipe.

The distribution of sediment particles within the pipe also appears uneven, with particles accumulating within a range of 0–148.1 cm for the 1.2 mm particle size and velocity 0.49 m/s along the *X*-coordinate from the inlet side. This accumulation of sediment particles can have important implications for the overall flow dynamics within the system, potentially hindering the flow of other particles and leading to increased sediment accumulation.

5 Conclusion

Insights regarding the composition and longevity of silt particles in the sewer system were gleaned from the study's findings.

1. The maximum *X*-coordinate is larger for smaller silt particles, suggesting that they are able to move farther through the sewage pipes. In contrast, sedimentation moves closer to the water flow entrance as particle size grows because the maximum *X*-coordinate falls with increasing particle size.
2. Particles sediment farther away because the torque moment imparted on them increases as the water flow velocity rises. The strength of the correlation between particle size and velocity increases with bigger particles.
3. Third, the research shows that raising the water flow velocity may lessen the severity of particle deposition. According to these results, keeping the flow rates up may assist keep the sewers clear and the water flowing smoothly.
4. Two solutions are presented to reduce the likelihood of sewage line clogs due to silt accumulation:

- First, increasing the magnitude of water velocity, and thus, improving the sediment transport, enables particles to silt at larger distances along the *X*-coordinate when the diameter of the sewer network is reduced to a suitable size.
- Second, the way to reduce the sediment amount and the possibility of blockages is to install filters in the sewage network to stop bigger particles from entering the system.

These suggestions are meant to better manage sedimentation, which, in turn, will increase the efficiency and lifespan of the sewage system as a whole. However, further study is needed to assess the viability and practical ramifications.

Author contributions: MAK was instrumental in the conceptual design and assembly of the sediment sediment transportation device; played a crucial role in collecting, analyzing the data, and conducting numerical analyses; was responsible for writing the thesis and manuscript, ensuring that the findings of the research were accurately and comprehensively documented. BKN contributed significantly to the experimental design of the device; provided invaluable guidance and supervision to MAK during the analysis of sediment transportation, ensuring the accuracy and reliability of our experimental procedures and results. WHH focused on the analysis of data and the results section. MAK, BKN and WHH were responsible for discussing the results, reviewing the thesis and research paper, and guiding the literature review proces; their insights were vital in interpreting the research results and situating them within the broader scientific context.

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Data availability statement: Most datasets generated and analysed in this study are in this submitted manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.

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