Experimental study of the effect on soil erosion of using tiny gravel as bedding for defective sewer pipes

H. H Khudhair 1*, Basim K N 2, J H Al-Baidhani 3
1 Civil Department, Basra Technical Institute, Southern Technical University, Basra, Iraq.
2 Civil Engineering department, College of Engineering, University of Kerbala, Kerbala, Iraq
3 Civil Engineering department, College of Engineering, Al-Nahrain University, Baghdad, Iraq
*Corresponding author: Email: hussein.hameed@s.uokerbala.edu.iq, +964 7712020437

Abstract. The erosion of soil is the most influential factor contributing to the creation of sinkholes in urban areas. Soil degradation often takes place due to failures in sewer pipelines, when water flows from and to the adjacent soil through pipes defects. Soil deficiency surrounding faulty stormwater sewer pipes has been attributed to various reasons, including water infiltration and exfiltration volume or discharge, crack size, relative density, water heads, and the number of cracks. This paper focuses on the effect of using tiny gravel media as a protective layer to reduce the processes of soil erosion due to the faults in the wastewater system, which is done by means of a comparison of erosion mechanisms observed when using a protective tiny gravel layer and without. A local sandy soil was used, obtained from the neighbourhoods near the city centre in the Karbala governorate. Sixteen tests, separated into two groups, were performed to identify the differences in outcome between the two statuses, with a matrix of various influential factors to which erosion has been attributed used across the experiments. The outcomes demonstrated that using a tiny gravel layer as a protective bedding layer has an excellent effect on impeding soil erosion processes and, in particular, tremendous efficiency in reducing cavity formation of up to 95.4%. Furthermore, the findings showed an 18.25 times decrease in the total eroded soil, while the settlement of soil surface showed a 26.35 times decrease, allowing higher internal stability and reduced sewer pipe path deformation.

Key words: tiny gravel, infiltration/exfiltration, stormwater sewer, cavitation, bedding efficiency.

1. Introduction
The formation of sinkholes is a major factor in soil failure, and sinkholes in urban areas offer huge risks to human life, including the potential for fatalities [13, 14, 27]. Several researchers [4–6] have noted the formation of sinkholes due to defects in sewer pipes causing internal erosion of soil, leading to serious damage to infrastructure as well as the aforementioned threat to human life. Furthermore, internal erosion of soil around sewer pipelines has been identified as a driver of the generation of underground voids [8, 12, 13]. Both structural and operational conditions of infrastructure, as defined by Chughtai et.al (2008) are thus exposed to this deterioration due to the formation of sinkholes [9]. Variation in climate over cities leads to varying water flow rate in their sewage systems, which can place extreme loads on defective pipes, increasing the possibility of the generation of cavities and inducing
high settlement levels [3, 15, 18, 25, 26, 29, 31–34]. Soil erosion cavities across sewer pipes may also lead to further failure of the pipe as a consequence of a lack of soil support [2, 7, 32, 35]. Such events have been noted in Guatemala, in Ottawa, and in many other places around the world [4, 5, 17, 39]. In that situation, the relationship between the grain size of the bedding materials and the defect size can be considered the main influencing factor for the erosion process. Rogers at (1986), suggested a relationship between bedding grain size to leak width (B/D₈5) and the soil erosion rate, where B is the sewer pipe crack width and D₈5 is the sieve size through which 85% of particles pass within the bedding soil sample. This study showed that the critical flow of soil through a leaky pipe begins when the defect width reaches 2.5D₈5 to 4.9D₈5[27], and similar results were found by Mukunoki [3]. Ghulam at (2018), used laboratory apparatus to investigate the effect of particle size and leak width impact on the erosion of local sandy soil and subbase type (D), showing that the eroded soil increased as the D₈5/B ratio declined. In general, the eroded soil reaches an eroded soil collection device quickly and continuously through leaks when the ratio of D₈5/B is less than 0.17 A model study to investigate the mechanisms of soil degradation induced by drainage pipe deficiency water infiltration was also created in [8].

The mechanisms for soil particle migration to various types of sewer pipe beddings, as specified by British Standards (1987), was examined by Fenner (1991) [28]; the findings of his study suggested the utilisation of bedding class-F (Flatbed) in preference to bedding of class-S (sewer pipe surrounded by granular material), as shown in Figure 1. The potential methods for reducing the existence of sinkholes based on soil settlement and ground loss suggested are thus to improve the internal stability of embedment materials to impede the erosion process (Sato and Kuwano, 2008) [6]; to detect cavity generation at an earlier stage by utilising geophysical techniques such as ground-penetrating radar (GPR) (El-Qady et al., 2005)[29]; or to avoid the occurrence or development of sewer pipe cracks. The first of these is often the most appropriate solution, as it reduces extra costs [30].

Pipe embedment and backfill products thus play a significant function in the migration of soils particles into faulty sewer pipes from a geotechnical point of view; an adequate balance of characteristics is thus sought to enhance the resistance of these bedding materials to internal erosion. An analysis of Australian sewer bedding material specifications revealed a lack of awareness of the importance of particle size distribution (PSD) in determining the susceptibility to erosion among those materials, however [41, 42]. Bedding material classification and descriptions have been studied by several researchers [1, 2, 22], with most such studies seeking to identify the effects of bedding thickness by applying analytical methods. Abolmaali derived a non-linear formula for soil erosion based on the finite-eliminate method (FEM) using Abaqus software [33], while Guo studied the erosion process for soils used as bedding materials by applying numerical model analysis to predict the rate of erosion for the soils [1]. Within this study, particle shape factor, particle size, void ratio, and submerged repose angle were identified as key soil properties and the groundwater table was the major function. Karouji investigated the subsidence of granular material (silica sand) under two water flux conditions, cyclic and continuous; his study outcomes revealed that a sequence of fast water supply and drainage cycles created quicker failure than slow water supply and drainage cycles [35]. Backfill materials have also been determined to play a crucial role in the total amount of soil subsidence and surface settlement [11,14]. Basim et al. further noted that, throughout the rainy season, water rises rapidly in the sewer pipe system, which leads to pipes operating under fully loaded conditions, thus accelerating cavity formation due to the increment of water volume quantities seeping through any cracks in sewer pipes, and consequently, increasing the infiltration water volume combined with the eroded soil accumulating inside the pipe through defects [16, 26, 30, 35, 38].

The current study aimed to identify the efficiency of using tiny gravel as a protective layer, and a small scale ground model experimental method was utilised to increase understanding of the impact of using such a protective gravel layer on the various mechanisms of soil erosion and subsidence. Image correlation using Particles Image Velocimetry (PIV) was employed to perform continuous observation of any soil subsidence.
2. Testing materials

The soil consisted of local materials derived from areas close to Kerbala city centre in the Karbala governorate. The soil samples were sieved to determine the soil grain size using a standard analysis method (Astm, 2007, Astm D-422). The soil size graduation is plotted in Figure 2, with further details shown in Table 1. According to the Unified Soil Classification System (ASTM D 2487-17), the resulting soil is described as sandy soil with poor graduation (SP). The soil permeability was also examined per ASTM D-1556.

The tiny gravel used in this study was intended as a protective layer of granular media to improve the soil resistance to erosion and subsidence, as shown in Plate 1. The properties of this gravel are presented in Table 2, and the particle size gradient per ASTM specifications is shown in Figure 3.

![Figure 1: Sewer bedding class (S) and (F) British Standards 1987.](image)

![Figure 2: Particle size distribution of experimental sandy soil](image)

**Table 1:** Experimental sandy soil properties

| Property                     | ASTM Designation | Value       |
|------------------------------|------------------|-------------|
| Specific gravity             | ASTM D854-14     | 2.60        |
| Coefficient of Gradation Cc  = $D_{60}/D_{10}$ | ASTM D2487-11   | 0.88        |
| Coefficient of Uniformity Cu = $D_{60}/D_{10}$ | ASTM D2487-11   | 3.18        |
| Plastic Limit (P.L)         | ASTM D4318-05    | 14%         |
| Liquid Limit (L.L)          | ASTM D4318-05    | 18%         |
| Plasticity Index (P.I) P.I = L.L - P.L | ASTM D4318-05   | 4%          |
| D75                          | -                | 0.571 mm    |
| Optimum water content        | -                | 8.56%       |
| Soil permeability            | ASTM D -1556-03  | 0.00021 m/s |
Figure 3. Particle size distribution of experimental tiny gravel

Table 2: Experimental tiny gravel properties

| Property                             | ASTM Designation | Value |
|--------------------------------------|------------------|-------|
| Specific gravity                     | ASTM D 3854-214  | 2.85  |
| Coefficient of Gradation Cc= D_{50}/D_{10} | ASTM D 2487-11   | 2.56  |
| Coefficient of Uniformity Cu= D_{60}/D_{10} | ASTM D 2487-11   | 1.03  |
| D_{75}                                |                  | 6.84 mm |

3. Experimental apparatus

The current study’s test apparatus was designed to overcome the disadvantages of the previous models, based on a review of the testing models and apparatus used by previous researchers [12, 19, 21, 24, 28, 37, 38]; it was thus built as big as possible to provide better simulation of real soil cavities’ formation and subsidence. The model is illustrated in Figure 4 and Plate 2. The apparatus was composed of a soil compartment, a gathering unit to collect the eroded soil, water inflow and outflow control valves, and some variable steel weights. The entire soil container had dimensions of 800 x 100 x 490 mm. Both the front and back walls were of 10 mm strengthened glass with steel framing, to allow observation of the development process of cavity formation through translucent walls. At the base of the soil chamber, five interchangeable erosion soil collection units were placed to facilitate changing the numbers of cracks and crack sizes, simulating various pipe defects near the crown. The water volume in each cycle could
be changed by adjusting the supply valve, and a rubber strip and an O-ring were placed between the soil chamber base and eroded soil collection units to prevent leakage from the connections. At the lower end of the soil gathering unit, a drainage valve was fixed that opened when discharge was required and closed during water supply.

By adjusting the steel loads placed at the top of a timber beam, the actual weight of soil was imitated for various depths of sewer pipe. A high stiff plastic pipe of a 2 mm radius was used to move water from the source tank to the valve, and for each particular water head, the water flow rate was calibrated and the volume over time measured.

Plate 2. Image of the experimental apparatus.

Figure 4: Schematic diagram of the apparatus

4. **Experimental methodology and procedure.**
The eroded soil collection unit with 8- and 6-mm replaceable crack width and 55 mm length was placed at the base of the soil chamber and held in place with screws, with the top surface of the collection unit and the bottom of the soil compartment at the same level. The defect length was placed in a direction parallel to the glass walls, then the tiny gravel layer was placed at the desired thickness and compacted by tamping. The soil was then added to the soil compartment as 70 mm layers that were then compacted to 75 or 85% relative density, depending on the test to be performed. Two water heads were utilised (1.7
and 2.0 m), and dry, 4%, and 8% soil initial moisture contents were investigated. Appropriate steel loads were set on a timber beam fixed on the soil upper surface to represent 1.5 m of soil depth over the sewer pipe. The model was left for 12 to 18 hours in each case to decrease implied creep impact before 0.9 or 0.3 litres of water was applied to the soil model through the crack, depending on the test. The drainage plug was removed after 3.5 min, permitting water and any eroded soil to flow out of the collection unit. The water supply and drainage process together created a cycle, and this was replicated fourteen times per test. Each cycle, the eroded soil was collected, dried, weighted, and then sieved. The Particles Image Velocimetry (PIV) was captured based on image correlation using a built in MATLAB software function, and this was utilised for continuous observation of the soil vertical displacement.

Nikon D5300 DSLR cameras were used with 23.6 x 15.6 mm complementary metal oxide semiconductor (CMOS) sensors and an image resolution of 6000 x 4000 pixels. To avoid relative movement between the lens and the target, which can occur in automatic mode due to auto focusing, the camera and lens were operated in manual mode; further, to avoid the reflection of nearby objects on the glass walls of the apparatus, which could disturb the images and hamper the correlation process, black covers were used behind the camera [39], which was initially placed in close vicinity to the target; however, as this created perspective distortion in the images [39], the maximum possible distance of 1.5 m was selected.

5. Outcomes and discussion.

According to the Iraqi general standards for the implementation and installation of sewer pipe systems, utilisation of granular media as embedment materials is recommended. Consequently, it is essential to investigate the effects of such granular particles on erosion and subsidence processes. In this study, tiny gravel was used as a protective layer above pipe cracks, rather than as an entirely embedded material, in order to identify the effectiveness of utilising a granular media as a protection layer for pipelines in sewage systems. Various tests were thus performed in different conditions, with two cracks widths of 6 and 8 mm, two water pressures of 1.7, and 2.0 metres, initial moisture content varying between dry, 4%, and 8%, relative density of 75% and 85%, also two water fluxes, 0.3 and 0.9 L. Cases with one, two, and three cracks were also investigated.

Figure 5 reveals that employing the small gravel media had huge impacts on the cumulative erosion soil weight, and the overall cavitation process. The results show a decrease in eroded mass volume of 18.25 times for a single crack on using the tiny gravel layer, and a similar influence was noted even in the multi-crack case, with the reductions being 25.84 times and 30.62 times for two or three defects respectively, as displayed in Figure 6. Based on observations that no cavity formation or high subsidence occurred either in single or in the multi-cracks cases, the tiny gravel appears to offer protection based on its effect as a filter, preventing the soil particles from flowing along with the water seeping into the defective pipe.

![Figure 5](image-url): Cumulative eroded mass with and without gravel layer in various test cycles
Figure 6: Eroded soil mass with and without gravel layer in different cycles for multi crack statuses.

It was also highly notable that the decrease in the erosion in cases of two and three cracks with spacing equal to 55 mm, which had the highest probability of cavity creation as mentioned in the preceding figure, showed only small values of eroded mass due to the behaviour of the tiny gravel layer restricting cavity formation by reducing the motion of the particles. This state also registered the least subsidence, as shown in Plate 3. Thus, the possibility of cavity generation and soil surface settlement is noticeably decreased when the separating distance is increased, with no necessity for additional examinations for these cases.

Plate 3: Image for total settlement A) with a single crack and B) with four cracks in local sandy soil without a gravel layer
Experiments with two different defect widths (6 and 8 mm) and inflow volumes (0.3 and 0.9 L) were conducted to assess the performance of a tiny gravel layer with regard to different crack sizes and various water fluxes. The volume of eroded soil during the test cycles is shown in Figures 7 and 8, and the results reveal a significant decrease in soil erosion by 22.15 times for both crack sizes. The decrease in defect width from 8 mm to 6 mm without the gravel protective layer reduced erosion by 38%, while this effect was increased to 71% with the gravel layer. The overall decline in erosion based on adding the protective layer was 28.75 times for an 8 mm crack, supporting the restriction on negative behaviours in embedded soil around sewer pipes caused by screening using a tiny gravel layer.

![Figure 7: Cumulative eroded mass with and without gravel protect layer during tests for different leak widths. Iw=0%, and V=0.3L.](image1)

![Figure 8: The relationship between water volume and total eroded soil at water volume 0.9L](image2)
Furthermore, the soil final layer vertical subsidence was decreased by 26.35 times, with total subsidence reduced from 13.7 mm without the protection layer to 0.52 mm with such a layer, as shown in Plate 4. Figure 9 further reveals a decrease of 23.4 times water volume in the 0.9 litre case.

It was clear that increasing crack width and water quantity in the exfiltration/infiltration cycle did not have a significant impact on the erosion process and cavity formation; the general behaviour of the soil was also similar in terms of increasing the cumulative amount of eroded soil in cases with and without gravel layer.

Plate 4: The differences in subsidence between cases using gravel and without a tiny gravel protective layer

Two various water head experiments were performed to increase confidence in the performance of the tiny gravel layer, and another additional experiment at 75% relative density was conducted. The experimental results of these tests are shown in Figures 9 and 10. The results revealed that when the water head increased, the amount of erosion was correspondingly increased. In addition, when a comparison was made to examine whether utilising the protective layer was efficient and successful, a high difference in measured total eroded soil was observed, with a reduction of 5.491gm in the second case. This implies that the efficiency of erosion reduction can reach up to 95.4%.

Figure 9: Total cumulative eroded soil through various cycle tests in 2.0 metre water head with and without gravel protection layer
Similarly, the high impact of using a gravel protective layer was also seen in the lower density state, with total eroded soil volumes declining from 10,333.8 to 285.6 gm, equivalent to a 36.2 times reduction. Further, the soil with the protection layer did not fail and the soil erosion resistance continued until the end of the test, which was not the case without a gravel layer, as shown in Figure 10.

![Figure 10: Total eroded soil at the end of 14 cycles with 75% density during the experimental test.](image)

In general, the outcomes of the tests indicated a high impact of using a protective tiny gravel layer. Overall, the use of a gravel layer decreased the erosion of soil by at least 18.25 times, generating an efficiency of 95.4%. This confirms that the use of this procedure leads to an increase in the resistance of soil to cavity formation and subsidence.

6. Conclusion
- The results showed that the cumulative amount of eroded soil reduction was 18.25 times greater with a gravel layer than without.
- The overall decrease in soil surface settlement was 26.35 times.
- The total effectiveness of the employing a tiny gravel protection layer was 95.4% in all cases, including different heads; various defect widths; one, two, or three cracks; and even with varying relative densities.
- Due to the high efficiency of utilisation of a gravel protective layer with regard to impeding both subsidence and erosion process, as shown in this study, this capability of reducing soil erosion should control deformation of sewer pipe paths where it is utilised.

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