Study on Erosion Mechanisms Caused by Leakage at Culvert Joints and Outlets

Nindya Fitri Sari[1]*, Hary Christady Hardiyatmo[1], Teuku Faisal Fathani[1]
[1]Department of Civil and Environmental Engineering, Gadjah Mada University, Yogyakarta, INDONESIA
**Corresponding author:* nindyafitrisari@mail.ugm.ac.id

ABSTRACT

Culverts play a vital role in facilitating water flow beneath roadways. However, leakage within culvert sections can undermine soil stability, potentially leading to pavement failure or sinkhole formation, posing serious risks to transportation infrastructure and public safety. Leakage commonly results from inadequate installation of culvert segments or structural deterioration of the outlet wall. Leakage at these locations weakens the soil structure, making it increasingly vulnerable to erosion over time. In this study, laboratory experiments were conducted to investigate the mechanisms of soil erosion in sandy soils induced by leakage at two critical points: the joint and the outlet. It specifically examines the effects of flow duration and outlet opening width on erosion progression. The results indicate that the erosion process follows three distinct phases: (1) initial erosion, characterized by water infiltration and soil weakening; (2) temporary stability, wherein the soil appears stable despite the gradual loss of particles; and (3) final erosion, resulting in significant structural degradation and potential sinkhole formation. Furthermore, the width of the joint opening follows a similar pattern, where a larger gap results in increased erosion. Conversely, when leakage occurs in the outlet wall, the quantity of material eroded in the joint region typically reduces.

Keywords: sinkhole, erosion process, joint leakage, inadequate installation, sandy soils, flow duration, outlet opening width.

ABSTRAK

Gorong-gorong memiliki peran penting dalam memfasilitasi aliran air di bawah jalan raya. Namun, kebocoran pada bagian-bagian gorong-gorong dapat melemahkan kestabilan tanah, yang berpotensi menyebabkan kerusakan perkerasan jalan atau terbentuknya lubang runtuhan, sehingga menimbulkan risiko serius terhadap infrastruktur transportasi dan keselamatan publik. Kebocoran umumnya disebabkan oleh pemasangan segmen gorong-gorong yang tidak memadai atau kerusakan struktural pada dinding outlet. Kebocoran pada titik-titik ini melemahkan struktur tanah, sehingga tanah menjadi semakin rentan terhadap erosi seiring waktu. Dalam studi ini, dilakukan percobaan laboratorium untuk menyelidiki mekanisme erosi tanah berpasir yang disebabkan oleh kebocoran pada dua titik, yaitu sambungan dan *outlet*. Penelitian ini secara khusus mengkaji pengaruh durasi aliran dan lebar bukaan outlet terhadap perkembangan erosi. Hasil penelitian menunjukkan bahwa proses erosi berlangsung dalam tiga fase yang berbeda, yaitu: (1) erosi awal, yang ditandai dengan infiltrasi air dan pelemahan struktur tanah; (2) stabilitas sementara, di mana tanah tampak stabil meskipun terjadi kehilangan partikel secara perlahan; dan (3) erosi akhir, yang menyebabkan kerusakan struktural signifikan dan potensi terbentuknya lubang runtuhan. Selain itu, lebar bukaan sambungan menunjukkan pola yang serupa, di mana celah yang lebih besar menyebabkan peningkatan erosi. Sebaliknya, apabila kebocoran terjadi pada dinding outlet, jumlah material yang tererosi di area sambungan umumnya berkurang.

Kata Kunci : lubang runtuhan, proses erosi, kebocoran pada sambungan, pemasangan yang tidak memadai, tanah berpasir, durasi aliran, lebar bukaan outlet

1 INTRODUCTION

Culverts are essential components of road infrastructure, utilized to direct surface or river water beneath the roadway. Damage to the culvert components may indicate a vulnerability that may lead to serious future issues. One major consequence of such damage is the formation of sinkholes, which pose a significant risk to road users. Pavement deterioration is often linked to water leakage at the culvert joints, including both segment connections and the outlet controls. These leaks typically occur due to improper installation of culvert segments (Kuswari *et al.*, 2024), the effects of traffic loads, or the aging of the culverts (Kuwano *et al.*, 2006). For instance, Hermosilla (2012) reported that a 30 m wide sinkhole appeared in Guatemala City in 2007, followed by another measuring 18 m in 2010, both attributed to sewer pipe leakage. Similarly, Kim *et al.* (2016) identified 3,328 sinkholes in South Korea between 2011 and 2014 caused by culvert leakage.

The Water Research Centre (WRc) in England introduced the concept of sinkholes triggered by erosion within drainage systems (Rogers, 1986). This phenomenon arises from the infiltration of groundwater or wastewater through damaged drainage pipes, particularly during and after periods of heavy rainfall. Water entering through these defects can mobilize soil particles, leading to the gradual weakening of the surrounding soil structure. As a result, subsurface voids may develop and eventually cause the sudden collapse of the road surface.

Various experimental studies have been conducted to improve the understanding of erosion mechanisms induced by culvert leaks (Davies *et al.*, 2001; Indiketiya *et al.*, 2017; Mukunoki *et al.*, 2009). The influence of hydraulic conditions, leak sizes, and soil particle size are among the critical factors for soil erosion that were analyzed. Furthermore, these studies have examined hydrological conditions such as infiltration–exfiltration cycles, continuous and repeated flow patterns, and variations in groundwater levels. For instance, Alsaydalani and Clayton (2014) indicated that exfiltration flow led to soil loosening in leakage areas. The discharge of the soil particles is caused by a fluidization process driven by water pressure through the leak gaps. Once loosened, the particles are transported back into the culvert by the water flow—a process referred to as infiltration (Kim *et al.*, 2016). This cycle can persist until the overlying soil loses support, potentially leading to surface collapse. Karoui *et al.* (2018) found that soil loosening progressed more rapidly under repeated flow conditions than under continuous flow. Moreover, groundwater levels also play a significant role, as they influence both the volume and extent of erosion (Guo *et al.*, 2013).

Building on the previous findings, the size and location of the leak within the culvert also significantly influence the rate and volume of soil erosion. Zhang *et al.* (2020) categorized leakage shapes into circular, elongated, and transverse apertures, found that circular apertures produced a more concentrated flow, resulting in greater sand erosion compared to other shapes. Tang *et al.* (2023) further emphasized that the location of the leak—whether at the crown, side, or invert of the culvert—plays a critical role in determining both the intensity and duration of erosion. In addition, improper installation of culvert segments has been identified as a contributing factor to joint leakage and erosion (Kuswari *et al.*, 2024; Sholeha *et al.*, 2024).

Based on previous studies, most existing studies have primarily focused on examining the erosion mechanisms occurring at culvert joints. Based on previous discussions, most existing studies have primarily focused on examining the erosion mechanisms occurring at culvert joints. However, until now, no research has specifically investigated erosion caused by leakage occurring at two points — the joint and the outlet of the culvert.

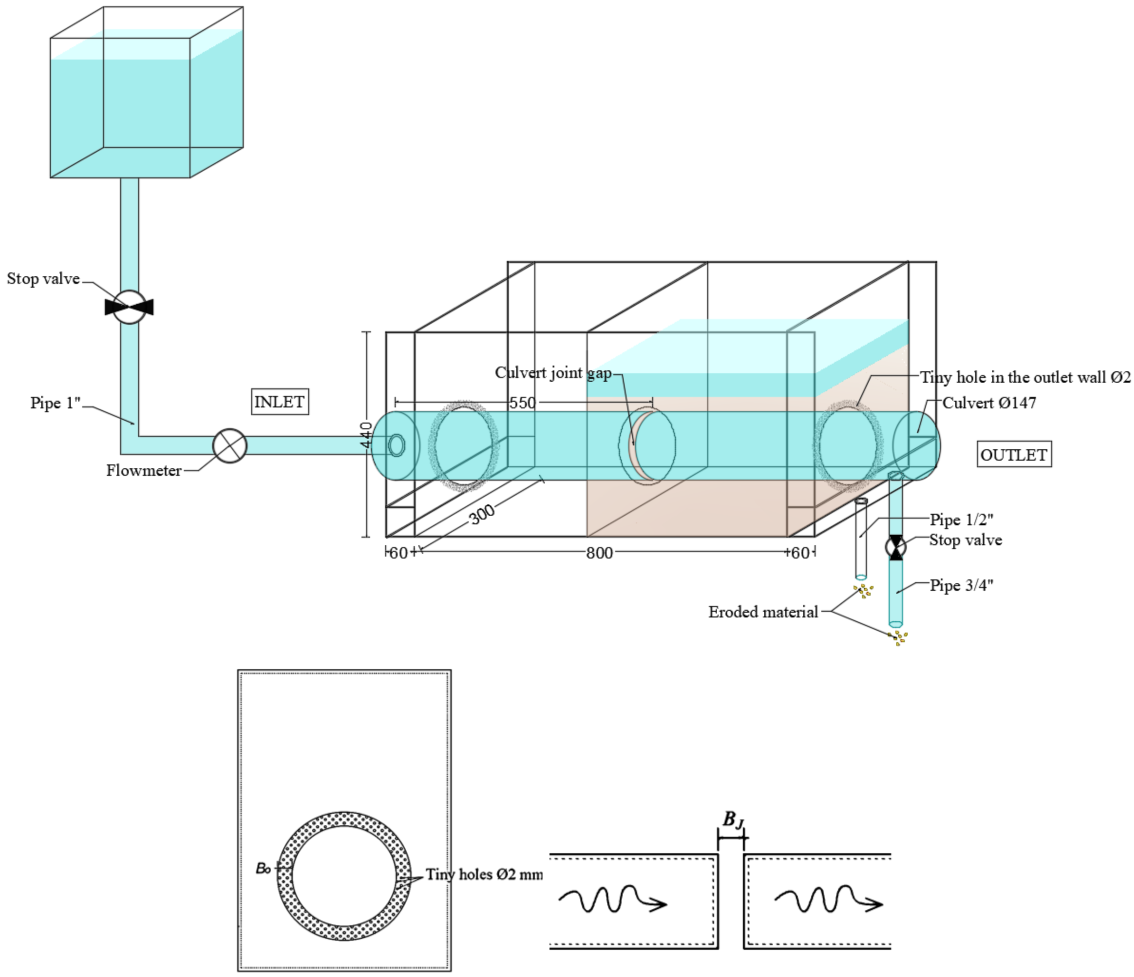
Accordingly, this study conducted experimental modeling in a laboratory setting to evaluate the influence of various parameters on the extent of erosion. The variables examined include flow duration, the width of leakage at both the joint and the outlet, as well as the characteristics of the soil used in the tests. The soil material utilized in this study is well-graded sand. The findings from this research are expected to provide a more comprehensive understanding of the erosion behaviors and mechanisms linked to dual leakage conditions, as well as their potential impact on the structural stability of culvert systems.

2 METHODOLOGHY

2.1 Experimental Setup

Figure 1 illustrates the testing equipment used in this study, which was adapted from the previous study (Kuswari et al., 2024) with a scale reduction of approximately 1:10. The apparatus was constructed of transparent acrylic to facilitate visual observation during testing. The soil box measured 30 cm in width, 92 cm in length, and 44 cm in depth. On the right side of the soil box, small holes with a diameter of 2 mm and an aperture of 20 mm were provided to simulate leakage at the culvert outlet.

To replicate outlet leakage, two interchangeable plates—identical in size to the right side of the box—were installed. These plates allowed for the adjustment of leakage opening sizes, which were set at 10 mm and 15 mm in this study. Water was supplied from a reservoir to the inlet using a 1-inch diameter pipe, equipped with a stop valve and flowmeter to ensure precise control of the inflow rate. At the outlet, two drainage pipes are installed: a 0.5-inch diameter pipe to channel water from the simulated outlet leakage and a 0.75-inch diameter pipe to drain water from the main channel.



(b) (c)

Figure 1. Experimental setup; a) front view; b) right view; c) detailed joint gap (not to scale, units in millimeter).

2.2 Material

The sand utilized in this study was obtained from Mount Merapi, and its properties were analyzed following the Indonesian Standard (SNI) 03-1968-1990 testing method. The results of the sieve test are shown in Figure 2, while the soil classification is presented in Table 1. When preparing the soil, water was added to achieve a moisture content of 10–12%, reflecting typical field conditions where the soil is not completely dry. The soil compaction process was conducted in stages by placing the soil in 5 cm layers until 30 cm of thickness was achieved. To ensure uniform soil density throughout the model, the dry unit weight *(γ_d)* was maintained within the range of 15–17 kN/m^3.

Table 1. Soil Properties of Merapi Sand

USCS Classification	SW (Well-Graded Sand)
Specific gravity *(G_s)*	2.779
D_{10} (mm)	0.150
D_{30} (mm)	0.380
D_{50} (mm)	0.700
D_{60} (mm)	0.950
Coefficient of uniformity *(C_u)*	6.333
Coefficient of gradation *(C_c)*	1.013

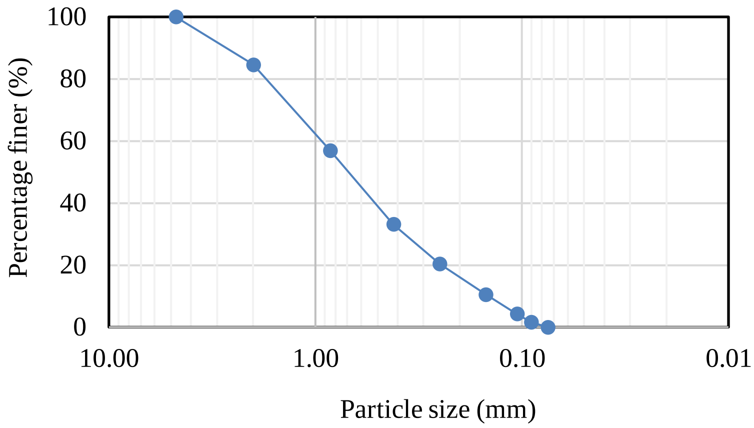


Figure 2. Particle size distribution.

2.3 Experimental Procedures

The experimental procedure is illustrated in Figure 1. The test began by opening the inlet stop valve while keeping both the outlet stop valve and outlet wall closed. Water from the reservoir was allowed to flow into the channel until it was filled. During this phase, gaps in the channel connections allowed water to leak into the surrounding soil, leading to a gradual saturation. The water level within the soil box was maintained at 5 cm above the ground surface to replicate saturated field condition. Once the saturation phase was complete, the outlet valve and cover plate in the outlet were opened, allowing water to exit through the joint gaps and small holes in the outlet wall. This outflow carried soil particles, initiating erosion. The eroded material captured using a No. 200 sieve was then dried, weighed, and recorded for further analysis.

The experiment was designed to investigate the effect of flow duration *(t)* on the weight of eroded material *(W)*. The experimental configuration employed a fixed joint gap width of 4 mm and varied the outlet opening width (B_o) at three levels: 0 mm, 10 mm, and 20 mm. Each test was conducted for flow durations of 10, 20, and 30 minutes, with a constant flow rate maintained at 19 L/min through continuous water flow cycle.

Further analysis was conducted to evaluate the effect of outlet opening width (B_o) on the amount of eroded material *(W)*, under varying joint gap widths (B_J) of 2 mm, 4 mm, and 6 mm. The outlet openings considered were 0 mm, 10 mm, and 20 mm. Each test was conducted for a maximum water flow duration of 30 minutes, assuming that the eroded weight would reach its peak within this time.

3 RESULTS AND DISCUSSIONS

3.1 Effects of Flow Duration

This study investigates the influence of flow duration on the quantity of material eroded under varying outlet opening conditions. Under controlled laboratory conditions, the research examines the relationship between flow duration *(t)* and the resulting quantity of eroded material *(W)*. The test results are presented in Table 2.

As illustrated in Figure 3, under the three outlet conditions—closed outlet, 10 mm outlet opening, and 20 mm outlet opening—the amount of eroded soil increased with longer flow durations. From 10 to 20 minutes, the increase was relatively moderate, but from 20 to 30 minutes, the erosion rate rose more sharply, indicating a nonlinear relationship between flow duration and erosion intensity.

Interestingly, Figure 3 also showed that under closed outlet conditions, the volume of eroded material was greater than in cases with outlet leakage. This phenomenon may be attributed to the concentration of flow through the joint gap, which enhances the detachment and transport of soil particles. In contrast, as the outlet opening widened, the flow of water became more evenly distributed, reducing the erosive force at the joint gap.

Moreover, the amount of eroded material at the joint is higher for the 10 mm outlet opening than for the 20 mm opening. This is likely due to the sustained flow through the joint gap, which directs particles toward the outlet.

However, as the outlet opening increases, the discharge capacity also rises, leading to a greater total volume of eroded material from both the joint and outlet wall areas.

Table 2. Effects of flow duration *(t)* on the weight of eroded materials *(W)*

No.	Outlet opening width,	Flow duration,	Eroded Materials,		Cumulative eroded materials,	Increase eroded materials,
			Joint	Outlet		
	B_o (mm)	t (minute)	W_1 (g)	W_2 (g)	$W = W_1 + W_2$ (g)	(%)
1	0	10	121.55	0.00	121.55	
	0	20	220.98	0.00	220.98	81.802
	0	30	607.58	0.00	607.58	174.948
2	10	10	112.86	10.27	123.13	
	10	20	162.83	13.02	175.85	42.817
	10	30	606.11	14.07	620.18	252.676
3	20	10	86.84	15.39	102.23	
	20	20	106.04	22.35	128.39	25.589
	20	30	427.09	23.68	450.77	251.097

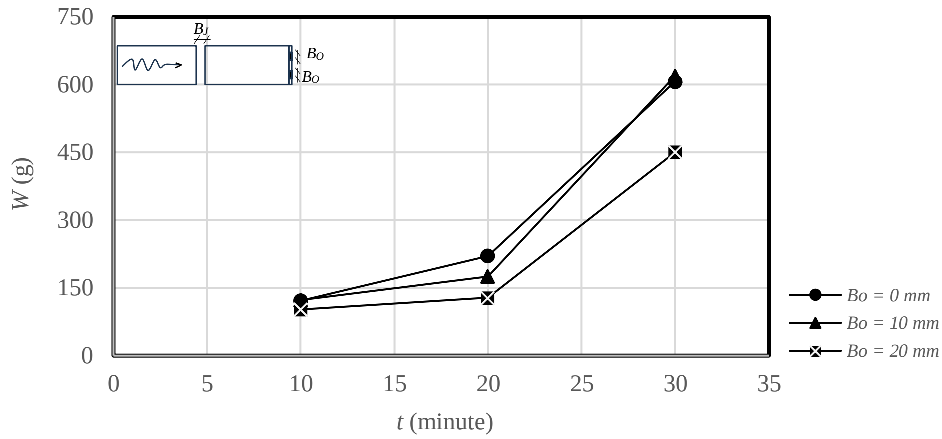


Figure 3. Effects of flow duration *(t)* on eroded materials *(W)*.

3.2 Effects of Outlet Opening Width

This study investigates the effects of the outlet opening width *(B_o)* on the weight of the eroded material *(W)*. The test results are presented in the Table 3. The findings illustrate the relationship between different outlet opening widths and the corresponding variations in the weight of eroded material, contributing to a more comprehensive understanding of how changes in leakage width affect the erosion process.

Table 3. Effects of the outlet opening width *(B_o)* on the weight of eroded materials *(W)*

No.	Gap width of culvert joints,	Outlet opening width,	Eroded materials,		Cumulative eroded materials,
			Joint	Outlet	
	B_J (mm)	B_o (mm)	W_1 (g)	W_2 (g)	$W = W_1 + W_2$ (g)
1	2	0	56.86	0.00	56.86
	2	10	43.07	10.68	53.75
	2	15	32.19	13.38	45.57
	2	20	23.44	21.59	45.03
2	4	0	607.58	0.00	607.58
	4	10	606.11	14.07	620.18
	4	15	439.64	16.98	456.62
	4	20	427.09	23.68	450.77
3	6	0	3103.31	0.00	3103.31
	6	10	2625.77	26.03	2651.80
	6	15	2501.97	30.03	2532.00
	6	20	2037.58	39.17	2076.75

Table 3 presented the influence of outlet opening width on the amount of eroded material in the presence of a leakage gap at the joint. As shown in Figure 4a, the amount of eroded material at the outlet increased with wider outlet openings. This phenomenon may be attributed to the higher water discharge through the outlet leakage, which enhanced the erosive force acting on the surrounding soil.

Conversely, Figure 4b revealed a different trend at the joint location. The presence of leakage at the outlet reduced the amount of eroded material at the joint. This reduction may be attributed to the redistribution of flow between the two leakage points, which dissipated part of the flow energy before reaching the joint. This mechanism aligned with the explanation provided in Section 3.1, where it was noted that multiple leakage paths can lower the erosion intensity at any single location.

Figure 4c illustrated the total weight of eroded material resulting from both leakage points. The data indicated that overall erosion may be primarily governed by the width of the joint gap. Although leakage at the outlet contributed to erosion, its effect was comparatively less significant than that of joint leakage.

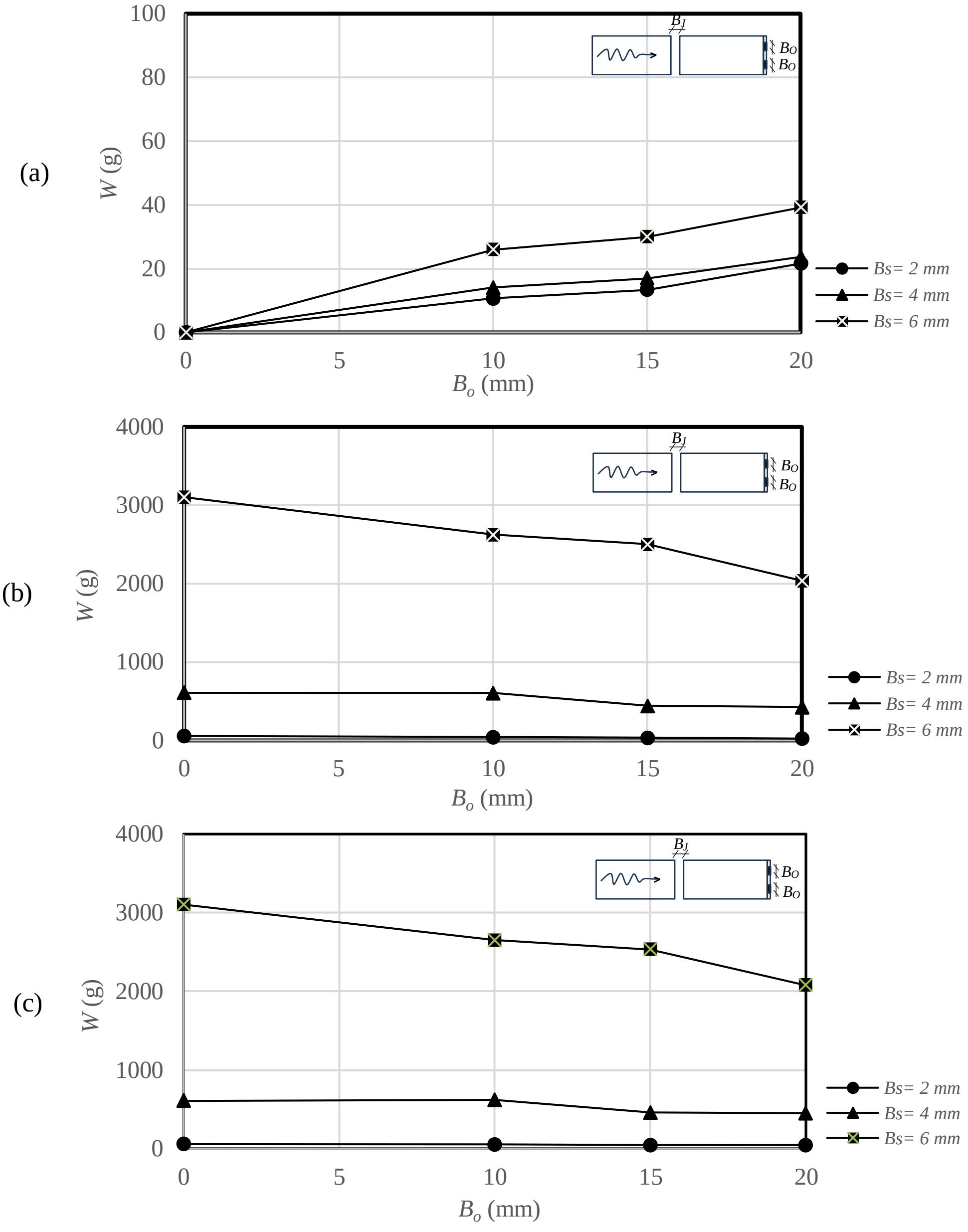


Figure 4. Effects of outlet opening width *(B_o)* on eroded materials *(W)*; a) at the outlet; b) at the joint; c) cumulative eroded materials.

3.3 Discussions of Erosion Mechanism

The test results demonstrate that flow duration and leakage width play a critical role in influencing the extent of erosion. The presence of two leakage points considerably heightens the risk of erosion and sinkhole formation compared to a single leakage point. The erosion pattern is governed by drainage time and progresses through three primary stages: the initial erosion phase triggered by saturation, the stabilization of the affected soil, and the final erosion stage, which ultimately leads to sinkhole formation.

In the initial phases of soil erosion, water infiltration and saturation around the leakage at the culvert joint initiate the displacement of sand particles. This process creates voids between soil particles and establishes a fluidization zone, where soil particles become detached due to the buoyant force exerted by the water flow. As a result, soil particles are transported, leading to the expansion of cavities and accelerating the erosion process. The formation of the fluidization zone alters the internal pressure distribution within the soil, potentially compromising the stability of the surrounding soil structure. This is the same as explained in the study conducted by Alsaydalani and Clayton, (2014) that the fluidization zone has an effect on the formation of early erosion.

In the next phase, as the flow duration increases, the erosion rate gradually decreases. This reduction occurs because most fine particles are carried away by the water flow, while the soil surrounding the leakage gap becomes more compact. Additionally, the remaining coarse particles contribute to the development of a more stable soil structure, creating a clogging effect that further slows the erosion process. This process is the same as that described in the study conducted by

However, the soil structure that appears to be stable can be disturbed once more if the water flow persists for an extended period. The remaining fine particles can be dissolved by water that continues to seep, resulting in the formation of new seepage paths. As the soil significantly loses its load-bearing capacity, the underground voids will continue to expand. If this process is not controlled, the cavity volume will continue to grow until the overlying soil can no longer support the surface load. At a critical point, the upper soil layer may suddenly collapse, resulting in the formation sinkhole.

The size of the joint gap and outlet opening significantly affects the mass of eroded material. In small gaps, fewer soil particles are transported due to obstruction by larger particles that exceed the gap size. Conversely, as the gap widens, material is more easily carried by the water flow, leading to an increase in erosion volume at larger openings. This is similar to research that has been carried out by Kuswari *et al.* (2024).

The existence of two leakage points can create flow interactions that influence the overall erosion pattern. In instances where leaks manifest concurrently at both the joint and the outlet, there is a possibility that some flow energy will be dissipated. This phenomenon may lead to a decrease in erosion in one specific area while simultaneously exacerbating it in another location.

4 CONCLUSIONS

The results of this study emphasize the significant impact of flow duration and leakage width on erosion severity. The presence of two leakage points considerably increases the likelihood of both erosion and land subsidence compared to a single leakage point. The erosion process progresses through three distinct stages: initial erosion caused by water infiltration and saturation, a stabilization phase in which the affected soil becomes more compact, and a final erosion stage that may lead to sinkhole formation. Throughout this process, the fluidization zone plays a crucial role by redistributing internal pressure within the soil, potentially compromising its structural integrity.

Moreover, the dimensions of the joint gap and outlet opening have a direct influence on the amount of eroded material. Smaller gaps limit soil particle displacement due to obstruction by larger particles, whereas wider gaps enhance erosion by allowing more material to be carried away by the water flow. Understanding these factors is essential for assessing erosion risks and implementing effective measures to mitigate the adverse effects of leakage-induced soil degradation.

REFERENCES

Alsaydalani, M. O. A., & Clayton, C. R. I. (2014). Internal Fluidization in Granular Soils. *Journal of Geotechnical and Geoenvironmental Engineering*, *140*(3), 04013024. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001039

Davies, J. P., Clarke, B. A., Whiter, J. T., & Cunningham, R. J. (2001). Factors in¯uencing the structural deterioration and collapse of rigid sewer pipes. *Urban Water*.

Guo, S., Shao, Y., Zhang, T., Zhu, David. Z., & Zhang, Y. (2013). Physical Modeling on Sand Erosion around Defective Sewer Pipes under the Influence of Groundwater. *Journal of Hydraulic Engineering*, *139*(12), 1247–1257. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000785

Hermosilla, R. G. (2012). The Guatemala City sinkhole collapses. *Carbonates and Evaporites*, *27*(2), 103–107. https://doi.org/10.1007/s13146-011-0074-1

Indiketiya, S., Jegatheesan, P., & Rajeev, P. (2017). Evaluation of defective sewer pipe–induced internal erosion and associated ground deformation using laboratory model test. *Canadian Geotechnical Journal*, *54*(8), 1184–1195. https://doi.org/10.1139/cgj-2016-0558

Karoui, T., Jeong, S.-Y., Jeong, Y.-H., & Kim, D.-S. (2018). Experimental Study of Ground Subsidence Mechanism Caused by Sewer Pipe Cracks. *Applied Sciences*, *8*(5), 679. https://doi.org/10.3390/app8050679

Kim, J., Choi, C., Kang, J., Baek, W., & Chung, M. (2016). Model test for the observation of cavity formation in sandy ground—With reference to ground water level and relative density -. *Japanese Geotechnical Society Special Publication*, *4*(4), 64–67. https://doi.org/10.3208/jgssp.v04.k02

Kuswari, S., Hardiyatmo, H. C., & Fathani, T. F. (2024). *Effects of Gap on Erosion Surrounding Culvert Joints—An Experimental Study*. *20*(2).

Kuwano, R., Horii, T., Kohashi, H., & Yamauchi, K. (2006, November). *Defects of sewer pipes causing cave-in's in the road*. In Proceedings of the 5th International Symposium on New Technologies for Urban Safety of Mega Cities in Asia, Phuket, Thailand.

Mukunoki, T., Kumano, N., Otani, J., & Kuwano, R. (2009). Visualization of Three Dimensional Failure in Sand Due to Water Inflow and Soil Drainage from Defective Underground Pipe Using X-ray CT. *Soils and Foundations*, *49*(6), 959–968. https://doi.org/10.3208/sandf.49.959

Rogers, C. (1986). *Sewer deterioration studies: The background to the structural assessment procedure in the sewage rehabilitation manual. WRc report ER199E*.

Sholeha, A., Hardiyatmo, H. C., & Ismanti, S. (2024). *Pengaruh Lebar Celah Pada Erosi Disambungan Saluran Berbentuk Persegi*.

Tang, Y., Zhu, D. Z., Chan, D. H., & Zhang, S. (2023). Physical and analytical modeling of soil loss caused by a defective sewer pipe with different defect locations. *Acta Geotechnica*, *18*(5), 2639–2659. https://doi.org/10.1007/s11440-022-01747-7

Zhang, D.-M., Du, W.-W., Peng, M.-Z., Feng, S.-J., & Li, Z.-L. (2020). Experimental and numerical study of internal erosion around submerged defective pipe. *Tunnelling and Underground Space Technology*, *97*, 103256. https://doi.org/10.1016/j.tust.2019.103256