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# EVALUATION THE IMPACT OF LEAKAGE SEWER ON INFRASTRUCTURE

A Thesis Submitted to the Department of Civil Engineering, University of Kerbala in Partial Fulfillment of the Requirements for the Degree of Master of Science in Infrastructure Engineering

By

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بِسم الله الرَّحمَن الرَّحِيم

# وَقُل رَّبِّ زِدْنِي عِلْمًا

**صدق الله العلي العظيم**

سورة طه الآية ﴿114﴾

# ABSTRACT

Sinkholes occurrences are repeatedly reported all over the world, and soil erosion process near defective sewer pipe is observed to be one of the conceivable reasons of these occurrences . Such accidents caused significant economic losses and presented a serious threat to human life. When water infiltrates into sewer pipes through the openings and cracks and other defects, the soil particles can be migrated into the sewer pipe with water leading to form cavities and eventually to a sinkhole. In addition, water exfiltration through the defects into the soil lead to the dilution of soil near the sewer pipe, which in turn leads to the process of soil erosion. The present study focused on the mechanism of soil erosion by water exfiltration/infiltration cycle through pipe defect and using dimensional analysis to develope a dimentionless model that predicts soil erosion of local soil.

Experiments were conducted using model tests to simulate soil erosion through a defected sewer pipe, where the experimental model involved soil exposed to cyclic water flow through leak located at crown of the pipe. The model tests were performed under varying matrix of influencing factors that affect the erosion procces such as: (1)leak with (2) soil particle size distribution (3)dry density of the soil (4)initial water content (5)the height of water level in soil (6)the flow rate through the leak (7)the number of cycle. Where the eroded soil is collected, dried, weighted and sieved for each cycle, cavity formation process was observed and evaluated during the tests under the different soil conditions. The present study investigated the ground settlement induced by erosion and the susceptibility of sewer pipe bedding material to erosion process. Where ground displacement of each flow cycle is tracked by image correlation using particle image velocimetry (PIV).

Results indicated that the soil particle size and the leak width was the most influential factors affecting the soil erosion induced by defected sewer pipe among the other factors. Where the amount of collected eroded soil is inversely proportional to the ratio of soil particle size to leak size. Results of the experiments and data analysis showed that the soil drains through the leak into the pipe easily and continuously when the ratio of soil particle size to leak size is less than 0.17, particle sizes less than 0.42mm are more prone to erosion and larger sizes are more resistant. Soil with 5% of initial water content has 7% more amount of eroded soil mass, while soil with 10% of initial water content has 16% more amount of eroded soil mass. In the study, pipe embedment material (subbase type (D) according to the Iraqi specification) was studied, and compared to the local sandy soil, subbase type (D) showed more resistance to erosion at rate of (50-90%) for different leakage sizes, where the local sandy soil were more susceptible to erosion under cyclic water flow. The dimensional analysis prediction model provide effective approaches to predict the behavior of soil erosion of local sandy soil.

## SUPERVISOR CERTIFICATE

I certify that this thesis entitled "Evaluation The Impact Of Leakage Sewer On Infrastructure" which is prepared by "Ali Nasir Ghulam" under my supervision at University of Kerbala in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering (Infrastructure Engineering ).

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V

*This thesis is dedicated to:*

*My parents and my family, brothers, sisters and friends for their love and continuous support*

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# CONTENTS

## LIST of FIGURES

# LIST OF TABLES

## LIST OF SYMBOLS

| Symbol | Definition | Dimension |
|---|---|---|
| B | Leakage width | L |
| C | Number of cycle | - |
| $C_u$ | Coefficient of Uniformity | - |
| $C_c$ | Coefficient of Gradation | - |
| $D_{70}$ | Soil particle size | L |
| $D_{max}$ | Maximum Particle Size of Soil | L |
| Es | Total Eroded Soil Mass | M |
| g | Gravitational acceleration | $L / T^2$ |
| Hw | Height of water level above the sewer pipe defect in soil | L |
| Q | Water flow rate through the leak | $L^3 / T$ |
| V | Inflow water volume | $L^3$ |
| W | Initial water content | - |
| ρ | Dry density of the soil | $M / L^3$ |

## ABBREVIATIONS/ACRONYMS

| | |
|---|---|
| ANOVA | Analysis of Variance |
| CT | Computed Tomography |
| DSLR | Digital Single-Lens Reflex |
| e | Residual |
| FWR | Foundation for Water Research |
| GPR | Ground Penetrating Radar |
| MAE | Mean Absolute Error |
| MAPE | Mean Absolute Percentage Error |
| MSE | Mean Square of Residual |
| MSR | Mean Square of Regression |
| PIV | Particle Image Velocimetry |
| RMSE | Root Mean Square Error |
| SPSS | Statistical Product and Service Solutions |
| SSE | Residual Sum of Squares |
| SSR | Regression  Sum of Squares |
| SST | Total of Sum Squares |
| WRc | Water Research Commission |
| WSA | Water Services Association |
| US EPA | United States Environmental Protection Agency |
| DEM | Discrete Element Method |

# Chapter One

## INTRODUCTION

### 1.1 Background

Ground surface collapses and Sinkhole accidents were widely reported around the world. Infrastructures in urban areas such as roads, highways or near buildings are the most frequent places where these accidents have been reported. The process of failure is usually happen suddenly and without warning or clear signs. This phenomenon increases the economic losses due to the interruptions of traffic and underground service lines, and also the negative effect of maintenance process. Furthermore, some collapses could present a serious threat to human life. For example, in Guatemala where 152 of people are killed due to sinkhole collapse in 2010 (Hermosilla, 2012) . In 2016 summer, a big sinkhole appearance occurred in Ottawa downtown Fig. (1-1), this caused an interruption of services like gas pipe leakage and failure of electricity lines. Similar appearances took place in china, where 19 sinkhole appeared in Shenzhen city in 2013, Fig. (1-2). There is a significant amount of capital losses in almost every sinkhole accident and this is in addition to the serious threat to human life. Depending on the nature and condition of the event, it may cause successive damages such as obstruction of the traffic and damage to the buried services, as well as damage to nearby buildings. The cost of repairing and the remediation of damages is usually high and can cost millions of dollars (Davies et al., 2001).


Figure 1-1 Photograph of a sinkhole accident occurred in Ottawa downtown, (BBC, 2016)

Figure 1-2 Rescue workers carry out the body of a victim in a road sinkhole accident in Shenzhen, China (Kaushik, 2013)

During the past decades, sinkholes formed in urban areas are often accompanied with the deterioration of buried pipelines. This type of sinkholes is different from the geologically known and defined sinkholes that can be found in karst formations or that which are formed in limestone. One of the most important mechanisms for the formation of this type of sinkholes is the loss of soil into the sewer pipes through the defects (Guo, 2013a). The process of soil erosion induced by defective sewer pipe and sinkhole formation got more attention recently. however, studies related to the mechanism of soil erosion and its interpretation to deliver an integrated understanding of the process are very scarce.

## 1.2 Statement of the Problem

The majority of studies that deal with defective sewer pipes often focus on the mechanical performance of the deteriorated sewer pipes, or on the estimation of the rate of water infiltration/exfiltration through the sewer pipes defects. However, the studies on soil erosion induced by defective sewer pipes is still preliminary. Incidents of sinkholes are increasing and result in a significant losses and serious risks. The present work is motivated by the urgent need to fill the gap between the large hazards of sinkholes and soil erosion studies. Soil erosion is considered to be an essential stage before the sinkhole appearance (Davies et al., 2001).

## 1.3 Objectives of the study

To achieve the main purposes of the present study, the following objectives have been satisfied:

1- Conducting an exhaustive review on the process of soil erosion induced by defective sewer pipes.
2- Investigating the mechanism of soil erosion due to water exfiltration/infiltration cycle through sewer pipe defect by conducting model experiments.
3- Developing a dimentionless model to predict the rate of soil erosion of local soil due to water exfiltration/infiltration cycle through defective sewer pipe.
4- Measuring the susceptibility of local sandy soil and subbase type (D) (which is sewer pipe embedment material according to iraqi specifications) to erosion by defective sewer pipe.

## 1.4 Study Scope

The present study will help in improving the understanding of soil erosion induced by defective sewer pipes especially, the local sandy soil which the present study focused on . Where the sandy soils is considered to be more prone to loss due to erosion than other cohesive soils, also the rate of erosion and the amount of soil loss become significant when the sewer pipe leak size is more than 2 mm (WRC, 2001). (Guo et al., 2013) stated that if the leak size is small, the soil would not be eroded with only water infiltration. In the present study, the experimental work was designed and executed using local soil and sabbase type (D) to examine the effects of different factors on the erosion, e.g., defect size, soil particles size distribution, initial water content, the volume of exfiltrated water and the relative density of soil. And by identifying the most important factors affecting the process of erosion in the present study by the experimental model, the dimensional analysis is important to find a statistical model to estimate the rate of soil erosion.

The present study introduces a new experimental methodology employing particle image velocimetry (PIV) to study the soil erosion process, soil movement and cavity formation near sewer pipe defects.

## 1.5 Thesis layout

Chapter 1 States the background, research problem statement, research objectives, scope of research works, and structure of the thesis.

Chapter 2 Chapter Two starts with a comprehensive review of soil erosion due to defective sewer pipes. Representative sinkhole accidents are analyzed to generalize a simplified model for the following modeling study. This chapter provides a foundation for the understanding of soil erosion by water infiltration/exfiltration through the pipe defect.

Chapter 3 Presents the properties of materials used in this study, material tests, apparatus design, testing procedures. Also, research methodology is presented.

Chapter 4 Dimensional analysis is utilized to find a statistical model to estimate the rate of soil erosion.

Chapter 5 Demonstrates the results of the study with extensive discussion

Chapter 6 Presents the main conclusions and recommendations for future work

# Chapter Two

# LITERATURE REVIEW

## 2.1 Introduction

This chapter presents a general overview on sewer management systems and the failure of the sewer system. Then, the chapter focuses on the studies conducted on soil erosion due to defective sewer pipes and some case studies of sinkholes induced by defective sewer pipes, then reviewing previous erosion apparatuses for soil erosion studies.

## 2.2 Sewer management systems

### 2.2.1 Gravity sewer system

This system is consisted from a network of buried pipes. The flow within the system pipes depend on gravity, therefore, each pipe must be placed in with an inclination. The inclination or the slope of the pipe should be sufficiently adequate so the flow has appropriate speed to prevent sedimentation of solid materials in the sewer pipe Fig.(2-1). Usually, sewer pipes network could not keep going in a slope all the way to the treatment plant due to topography restrictions. Therefore, pumping stations are used to overcome this problem. Furthermore, the process of digging deep trenches in the ground is very expensive; so, it is very appropriate to use pumping stations to raise the water and gain more elevation. Gravity sewers can carry both wastewater and storm water, or have separate pipes for both (Buchanan, 2010).

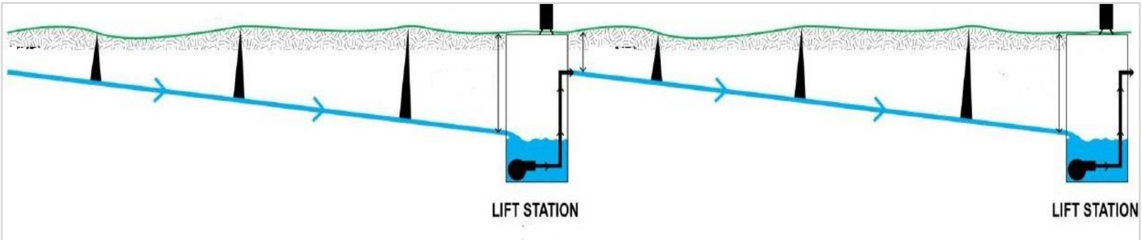


Figure 2-1 Typical gravity sewer and lift station profile (Gilbert, 2013)

#### 2.2.1.1 Separate sewer system

This system has a separate sewer network of each of wastewater and rain water. Since this system has two separate networks, the total cost of the two networks is high, and each network needs its own design. In spite of the higher cost, the separated system has other advantages to offer (U.S. EPA, 1999). (Baker, 2004), stated that the majority of combined sewer systems fail to deal with big rainfall storms and this results in combined sewer overflows. He mentioned that even though the separated system cost more, but it is the most effective way to prevent combined sewer overflows. Using separated sewer system leads to reduce flooding and splits the domestic sewage and prevents its flow into rivers, lakes, and so on. Thus, the ecosystem, the aquatic environment and the species living there are protected from pollution, bacteria and other pathogens coming from the domestic sewage (U.S. EPA, 1999).

Despite the fact that the separated sewer system delivers different advantages, it ought to be noticed that, if the surface runoff during wet weather are not handled, the effects of separated sewers probably won't be so convenient; particularly in urban territories (U.S. EPA, 1999).

### 2.2.1.2 Combined sewer system

This type of sewer network transfers rainwater, sewage water and in some cases the industrial wastewater. One of the most important problems experienced by this type of sewer network is the occurrence of sewer overflows when their capacity is exceeded during the rainy seasons. Capacity tends to fail because one cannot design the pipe to be too large (Baker, 2004). The high velocity of the flow induced by the amount of rainwater entering the network results in accumulation of sediments in the pipes (Field and Struzeski Jr, 1972) and increases water pollution significantly, this phenomenon is called the first flush. Combined sewer can be a good option, at least then when storm water discharges are not mitigated in an urban area (U.S. EPA, 1999).

### 2.2.2 Pressure sewer system

This system is basically a branched, small diameter pipe system was built underground with only visible parts being the storage tank’s lid and the control panel (U.S. EPA, 2002). It depends on small pump stations which are situated close to the residential units and other places from which the wastewater is gathered Fig.(2-2). This type of sewer system can be used when it is impractical to build other types of sewer systems like areas that are subjected to constant floods or have high water tables, or places which have topography that are inappropriate for using gravity sewer. The pressure sewer system might be small in size which includes only several residential units or might be large where can involve hundreds of pump stations.

Sometimes, a number of residential units is connected to one pump station (Strandberg, T., Hedmark, P., Held, H., 2010).

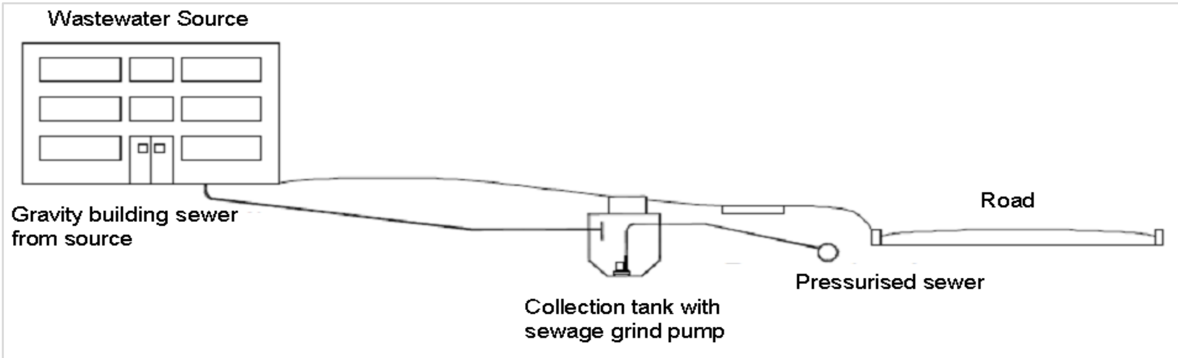


Figure 2-2 Schematic design of a pressurised sewer system, (WRF, 2010)

## 2.3 Failure of the Sewer System

The sewer system is the infrastructure that conveys domestic, commercial, and industrial sewage to wastewater treatment facilities. With an increase in population and industries, the system's capacity becomes limited, and it can ultimately fail. Many factors can also contribute to this failure. Structural defects of the sewer system often occur due to natural ageing, hydrogen sulfide ($H_2S$) crown corrosion, defective design and construction, excessive overburden, soil settlement, and earthquakes (Ly and Chui, 2012; Shin, 2012; USEPA, 1991). Sewer pipe failure is manifested by cracking, lateral deflection, crown sag, offset joints, deteriorated mortar, and exposed reinforcing caused by H2S corrosion (USEPA, 1991).

Two major concerns arise from deteriorated sewer pipes: infiltration and exfiltration. Infiltration occurs when groundwater enters the sewer system. This phenomenon is problematic because clean water is unnecessarily sent to the treatment plant, simultaneously decreasing the local groundwater table and increasing the cost of wastewater collection and treatment and the hydraulic loading at collection and treatment facilities (Doshi, 2012; USEPA, 1991). The emphasis on sewerage issues has nearly always been on infiltration (Ellis et al., 2004). However, exfiltration can be significant as well. Exfiltration occurs when sewage leaks out of the system and contaminates the surrounding groundwater and neighboring soil (Doshi, 2012; Ellis et al., 2004; Ly and Chui, 2012b; USEPA, 1991). Many studies investigated sewer exfiltration, its consequences (e.g. soil erosion, microbiological and chemical contamination of the surrounding groundwater and soil), and methods to quantify it (Ly and Chui, 2012a).

## 2.4 Quantification of Sewer Exfiltration

Different methodologies were developed to quantify sewer leakage. Some studies attempted to identify the presence of microbial and chemical contaminants in groundwater (e.g. ammonia, boron, chloride, nitrate, phosphate, and bacteria) as a way to prove sewer leakage (Cronin et al., 2006). However, the presence of these markers for sewage does not necessarily indicate sewer leakage. Other studies looked at factors that influence leakage and groundwater contamination (e.g. exfiltration rate, colmation layer) (Ellis et al., 2009). Another approach is to accurately estimate sewer leakage using both direct and indirect methods (Ly and Chui, 2012a; Rieckermann et al., 2007). Rieckermann et al. (2007) opted for a direct method of continuously dosing tracers in the sewer system, performing a mass balance on the tracers, and conducting an uncertainty analysis. A recent researchers, Ly and Chui (2012) suggested, instead, the use of numerical modeling to understand the complex behavior of sewer leakage. Their model would also predict sewage migration in the subsurface.

## 2.5 Studies on Soil Erosion Induced by Defective Sewer Pipes

Soil erosion due to defective sewer pipes has been addressed by limited studies. Most studies on internal erosion focus on dams which is also recognized by other researchers (Alsaydalani and Clayton, 2014; Cui et al., 2012; Sato and Kuwano, 2015a). Other studies addressed the process of soil erosion by water infiltration through pipe defects (Guo et al., 2013; Mukunoki et al., 2012; Mukunoki et al., 2009; Sato and Kuwano, 2013, 2015b) , whereas other researchers studied the mechanism of soil erosion induced by continuous water exfiltration through buried pipes defects (Alsaydalani and Clayton, 2014; Cui et al., 2012, 2013, 2014; He et al., 2017). Soil erosion by water exfiltration can occur on any of sewer pipes or on water supply pipes, however, soil erosion by water infiltration through sewer pipe defects lead directly to soil loss. These two types of soil erosion ( erosion by water infiltration and erosion by water exfiltration ) have different mechanisms, each one will be presented separately after reviewing the parameters influencing soil migration through pipe defects.

### 2.5.1 Studies on the Parameters that Affect the Mechanism of Soil Migration Through Pipe Defects

The mechanism of soil erosion through pipe defects and soil subsurface erosion was studied by a number of researchers. Several parameters are found to be potentially important. Soil particle size distribution, the width of the leak in a sewer pipe, ground water infiltration / exfiltration through sewer pipe defects, the vacillation of the groundwater table and the density and the plasticity of the soil are among the most important parameters that have been found (Fenner, 1991; Guo et al., 2013; Kuwano et al., 2012; Mukunoki et al., 2006, 2007, 2012; Mukunoki et al., 2009; Otani et al., 2000; Rogers, 1986; Samanthi Renuka, 2012; Sato and Kuwano, 2008, 2013, 2015a, 2015b).

Leak width ( defect size ) is a key factor which determines the amount of eroded soil, soil lose is related to the ratio between leak width or width of the opening and the soil particle size (Rogers, 1986; Mukunoki et al. 2012). (Rogers, 1986) studied the soil erosion through pipe defects for fine sands and gravels and found a relationship between the ratio of leak (defect or crack) width to the size of the soil particles ($B/D_{85}$) and the amount of soil loss, where: (B) is the leak width and ($D_{85}$) is the size of the sieve through which 85% of the soil sample will pass. He found that the continuous migration of soil through the pipe defect occur when the leak width have a value of $2.5D_{85}$ to $4.5D_{85}$ or more. For freely flow sand under gravity (Kamel, 2008) observed a reduction in volume of soil loss as the particle to opening size ratio ($D_{60}/B$) increased Fig. 2-3, where ($D_{60}$) is the size of the sieve through which 60% of a soil sample will pass and (B) is the opening size. It was also observed that the location of the hole has a significant effect on the rate of sand movement into the pipe. A very small ratio or no sand erosion was observed for the case where the hole was located at the springline of the pipe. As the induced hole is moved towards the crown, more sand eroded into the pipe the maximum erosion was measured at the pipe crown (Fig. 2-3). (Mukunoki et al.,2012) studied the failure of soil (for fine sand and gravels) due to defective underground pipe and demonstrated that the critical value of leak width is $5.9D_{max}$, where: ($D_{max}$) is the maximum particle size of the soil. From both studies it can be concluded that for continuous soil erosion, the leak width must be greater than the maximum particle size of the soil.

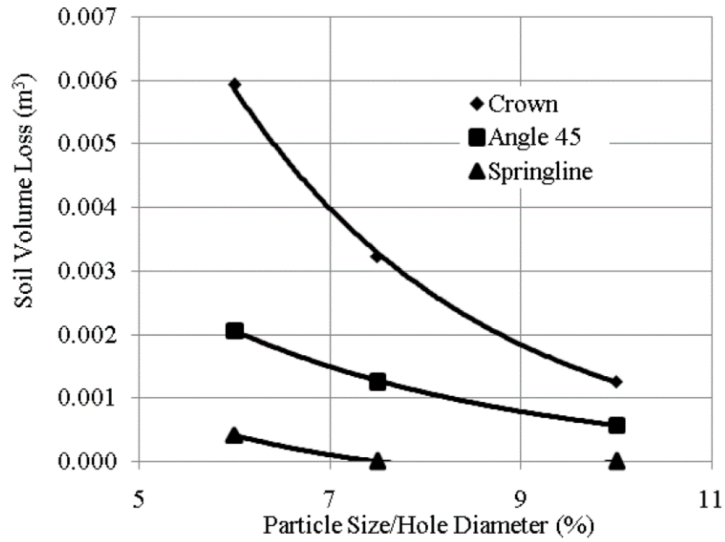


Figure 2-3 Ratio of Backfill Particle Size to Induced Opening Size Effect on Normalized Volume(kamel, 2008)

The internal stability of the soil is considered to be on of the key factors that affect the rate and the amount of soil loss. The term internal stability refers to the ability for the coarse fraction of a soil to prevent the loss of its fine fraction due to seepage flow. This factor was extensively studied (Burenkova, 1993; Chang and Zhang, 2013; Kenney and Lau, 1986; Yang and Wang, 2017). Summarising these findings, Kenney and Lau 1985 studied cohesionless, granular material soil and proposed a method for evaluating the potential for grading instability based on the shape of a material's grain size curve, he stated that the surest method for determining whether or not a granular material is potentially unstable is to perform a seepage test but, as an alternative, a geometrically similar grading would be acceptable. Chang and Zhang (2013) studied the internal stability of well-graded and gap-graded soils, they found that internal stability rely on hydraulic conditions of the soil (i.e.,, water content, hydraulic gradient ), physical conditions of the soil (i.e., particle size distribution) and mechanical situation of the ground (i.e., compaction, cohesion). They concluded that well graded soils more resistant to internal erosion than poorly graded soils. Yang 2017 studied piping failures in soils with different gradations. He found that the piping failures of internally stable soils were consistent with an effective stress equal to zero. In the case of internally unstable soil (i.e., gap-graded sand), a piping failure occurred in the form of internal erosion of fine particles, which were vigorously eroded out by the seepage flow.

Several researchers studied the effect of relative density of soil and they found that soil with high relative density is more resistant to cavity expansion and soil erosion in granular soils (Oh et al., 2016; Samanthi Renuka, 2012; Sato, 2010). Sato and Kuwano 2010, investigated the process of cavity formation in soil and how it progresses up to the ground surface and they found that the cavity expanded faster and the amount of soil loss increased rapidly at lower relative density. Renuka 2012, studied variation of mechanical features of loosened sand which accompanied with internally formed cavities, they reveald that soil with higher relative density is more sesistand to cavity expanding than loose soil. Oh Dong-Wook 2016 studied the influence of sewer fracture on ground surface in various relative density of sand, thier rsults showed that sand with low relative density caused much greater surface settlement compared to dense soil. On the other hand, (Rogers, 1986) and (Benahmed and Bonelli, 2012), revealed that a high proportion of clay in the soil and a low water content can increase erosion resistance, also they found that the relative density in clay materials has no significant impact on the erosion resistance.

All sewer pipes require proper bedding so as to have adequate structure support to ensure that theire long term structural performance is in accordance with the assumptions made during the structural design analysis. The bedding also facilitates the laying of pipes to the required line and level (WSA/FWR, 1993). (Jones, 1985), studied pipeline design and materials. He described how inadequate attention to bedding material choice is relation to native ground conditions is a common cause of sewer structural failure. An extreme example was cited in the use of 40 mm aggregate in a native ground consisting of silty sands with a high water table, water flow within the bedding causing the erosion of supporting soil from around the sewer. The type of bedding used around the pipe affect the extent and size of soil loss due to soil erosion, where water movement is easier in the granular material which allows fine materials of the soil to be washed out by water, and this means using granular material to surround a pipe will increase the erosion of the backfill soil. (Rauch and Stegner, 1994), examined the performance of infiltration of wastewater into the groundwater due to leaks in sewer systems. They found that the grain size of the bedding material had a strong influence on the exfiltration rate, larger particles allowing a higher flow rate. Therefore, the majority of specifications suggest that the pipe bedding material should be surrounded with a geotextile to prevent the migration of fines into the bedding zone from the backfill soil (Water Services Association Australia, 2002). Moreover, (Fenner, 1991), used different types of pipe beddings defined by the (British Standards Institution, 1987) to explore the mechanism of soil migration. Based on the results and observations of the ground settlement and the soil loss, they demonstrated that class-F bedding is recommended and more preferred than Class-S bedding (the pipe is fully surrounded by bedding material).

### 2.5.2 Soil erosion induced by water infiltration

Mukunoki et al. (2009, 2012), conducted laboratory model tests to explore the mechanism of road subsidence. Based on statistical data that collected in Japan. They showed that the majority of the accidents occurred during the rainy season Fig. (2-4) . also, they found that the number of road subsidence increased from 1980 almost linearly till 2005 Fig. (2-5). Collected data almost correspond to over 40 ages of underground pipes installed. They explained that during heavy rainy season, rain water flew into the underground pipe as sewerage pipes and the pipe would be filled with rain water with high pressure. Then, it can be considered that water infiltrated into the ground or were drained through or into the defective part, where it was assumed that the road subsidence is formed due to the drainage of water and the migrated soil into sewer pipe through pipe defects.

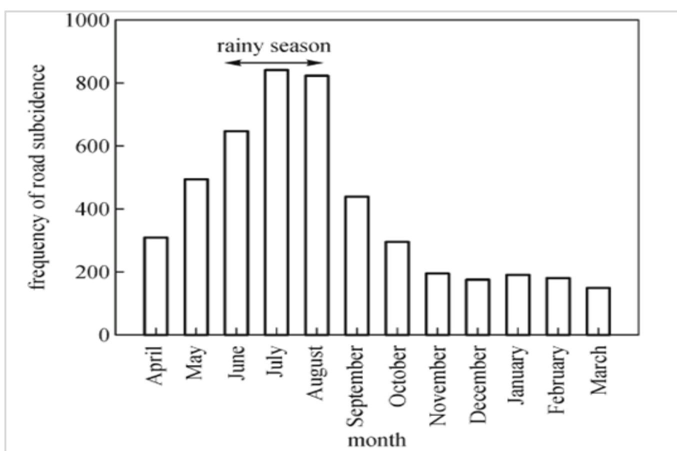


Figure 2-4 Frequency of road subcidences in each month of the year in Japan (Mukunoki 2012)

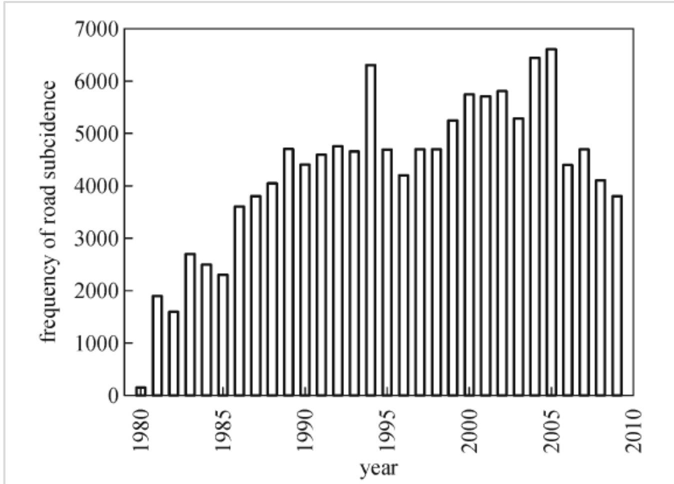


Figure 2-5 Frequency of road subcidences from 1980 to 2010 in Japan (Mukunoki 2012)

Their study continued with the laboratory model experiments, X-ray Computed Tomography (CT) was used to observe the process of cavity formation in the model, this model contained an experimental defective pipe which was buried in sandy soil under different water situations. They found that the monotonic flow of water infiltration led to form a flow path and weaken the soil but it did not form a cavity. They also found that the cyclic flow behavior of water through pipe defects (exfiltration/infiltration) lead to fatal failure in the soil. CT images showed low density area being already generated around the centre of the model ground in the 1$^{st}$ cycle of water inflow-soil drainage through the defect , the decreasing in the density of the area developed due to increasing the number of cycles. Granular material was spotted having interlocking behavior above the pipe defect. Also, they revealed that one of the factors causing the soil cavity formation is the loss of capillary force in the soil.

Sato (2010), conducted a number of laboratory model experiments imitating the flow of water and soil into the buried sewer pipe through the defect to explore the process of sinkhole accidents formation. He used a model consists of a small box of dimensions 5cm wide, 20cm high and 30cm in length with 0.5 cm opening located at the base of the box which was filled with soil. This model was exposed to repeat cyclic water flow (exfiltration/infiltration) through the opening. Where at first 0.1 litre of water was provided to flow out of the defect to the soil, then after stopping 1 minute, the drainage valve was opened to give the water and soil a chance to flow out. In case that 0.1 liter was insufficient to expand the cavity, the amount of supplied water was enlarged to 0.4 litre. He revealed that the way of cavity formation and expansion did not significantly affected by the overburden load above the pipe, and the cavity in the poorly graded coarse sand can expand rapidly. the typical cavity found was fan shaped with a slop on both sides and arching over the top Fig. (2-6), and the weight of lost soil increased with the enlargement of the cavity.

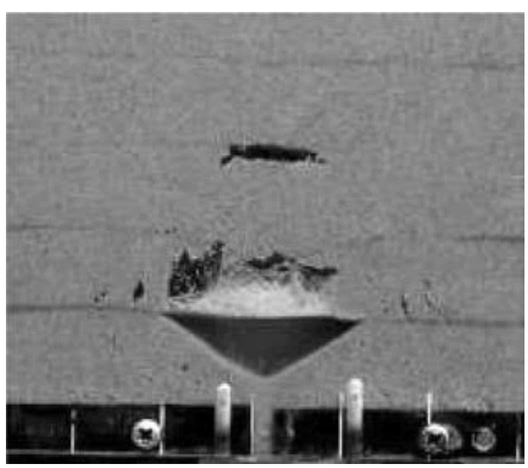

Figure 2-6 Typical forms of a cavity (Sato 2010)

Also, he revealed that the amount of soil for the monitored cavity is constantly less than the amount of the eroded soil collected draining from the model ground, and this shows that the soil is not only eroded from within the cavity but also from the surroundings Fig. (2-7).

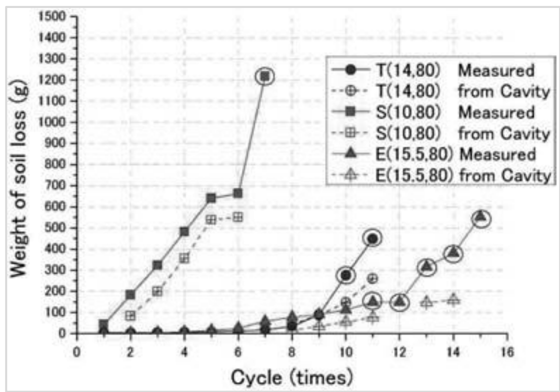


Figure 2-7 Comparisons “between measured soil loss and calculated soil amount equivalent to cavity volume” (Sato 2010)

Guo et al. (2013) investigated the process of soil erosion due to water inflow through pipe defects by laboratory model experiments. This model consists of tanks which have orifices located at the walls and the bottom of the tanks Fig. (2-8). The model was filled with granular soil to simulate the soil erosion through defects with different locations. The height of soil, the level of water, defect size and soil particle size were under control during the experiments. Shape of the void that was formed by the process of erosion were captured, water flow rate and soil flow rate through the defect were measured during the tests. After analysing their results, they divided the process of erosion into three stages. Stage one: at this stage, the soil began to erode and ended with the failure and subsidence of the soil surface. Stage two: at this stage, the subsidence was expanding until the water level descended below the surface of soil. Stage three: at this stage, water continued to seep through the soil without noticeable erosion. The authors also revealed that the geometric shape of erosion cavity was effected by soil and water height. While, the soil rate of flow through the defect was effected by the defect size and soil particle size. Depending on the free fall model by (Hilton and Cleary, 2011), the authors presented a prediction model to estimate the flow rate of water and soil through defects. More recently, (Guo and Zhu, 2017), proposed an analytical model to predict the soil and water flow rate through the pipe defect. This model was derived based on the Beverloo's equation (Beverloo et al., 1961) which takes into account the difference in the water pressure during the process of soil erosion. Proposed model was proved by comparing with the results of (Guo et al., 2013).

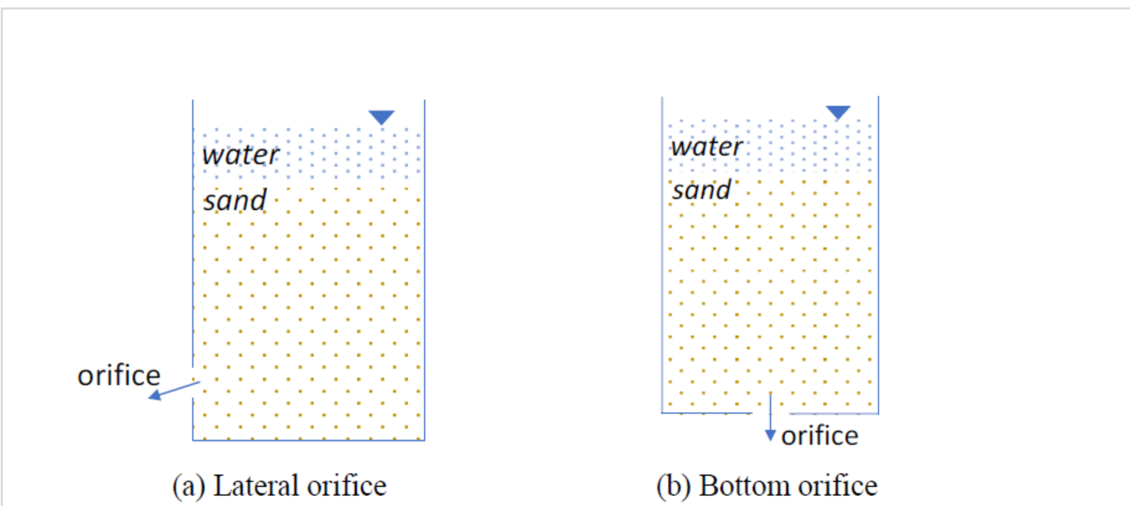


Figure 2-8 Schematic of experimental models (Guo et al., 2013)

(Sato and Kuwano, 2013, 2015), conducted model experiments to explore the process of soil erosion due to water infiltration through sewer pipe defect. They found that the soil is discharging into sewer pipes through defects during water seepage and at the end stage a sinkhole is formed Fig. (2-9). Based on the modeling experiments, they indicated that soil near to the pipe defect becomes loose and that developments in the loose ground were induced without the accompaniment of visible deformation, and the permeability of the soil was noticeably increased.

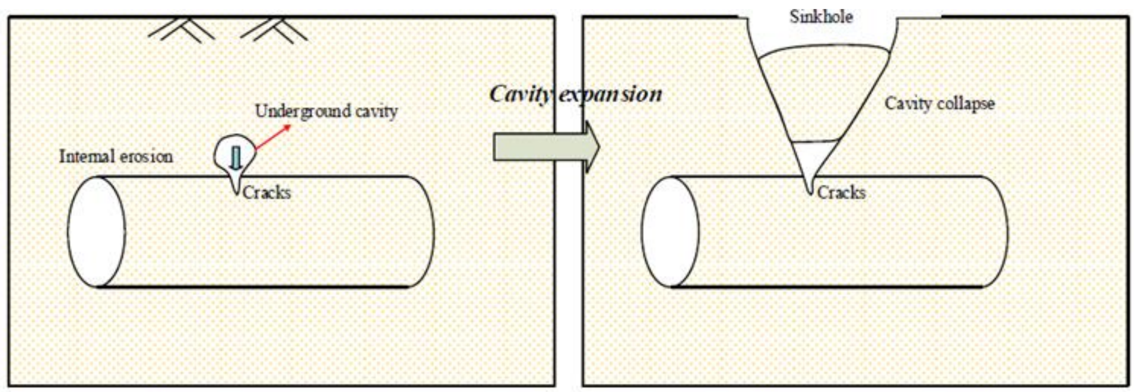


Figure 2-9 Schematic figure of sinkhole formation and internal erosion due to the defective sewer pipes (Sato and Kuwano, 2015)

Recently, Kim et al., 2016, used an experimental model that contains a rainfall simulator and a buried defective pipe. They revealed that the water level have greater impact on the process of soil erosion compared to the relative density of the soil. (Chae et al., 2016) performed 3-D Ground penetrating radar (GPR) surveys using the stream EM device equipped with a 38 channel multi-antenna were performed to detect ground cavities in Seoul. Their results showed that dozens of such cavities were found, and excavations were performed to investigate their cause. It was demonstrated that the main cause of cavity formation is the damage and the detachment of the aging sewage pipelines. They stated that an average of 677 road cave-ins occurred annually in the city of Seoul between 2010 and 2016. More than 70% of them occurred in the rainy season, with 78% of those caused by sewer pipe damage. Chae, 2016, olso conducted a series of model tests to investigate the mechanism of the cavity formation around sewage pipelines. Cyclic tests, in which the soil tank is saturated and then drained in multiple sequences, were performed, and the volume of the discharged soil was measured. The athors found that the rate of increase in soil erosion, road cave-in, and relaxation area was higher for soils with poor grain size distribution and lower fine particles content. Also, they stated, the causes of road cavein due to the formation of the cavity generated by the damage of the sewer pipe can be summarized as follows:

1. Increase in the groundwater level due to inflow of ground water into the ground.
2. Decrease in shear strength due to infiltration of groundwater.
3. Sediment discharge into the cracks of sewer pipeline.
4. Instability of the ground due to expansion of cavities.

Karoui et al., 2018, studied the factors affecting the mechanism of ground subsidence by physical modelling of a sewer pipe defect (Fig. 2-10). They revealed that the groundwater flow direction, hydraulic gradient around the leakage point, and strength of the ground to support itself were the main factors that dominate the mechanism of ground subsidence. Also, they found that the ground loosening caused by a succession of water supply and drainage cycles leads to a faster collaps than a continuous leakage system.

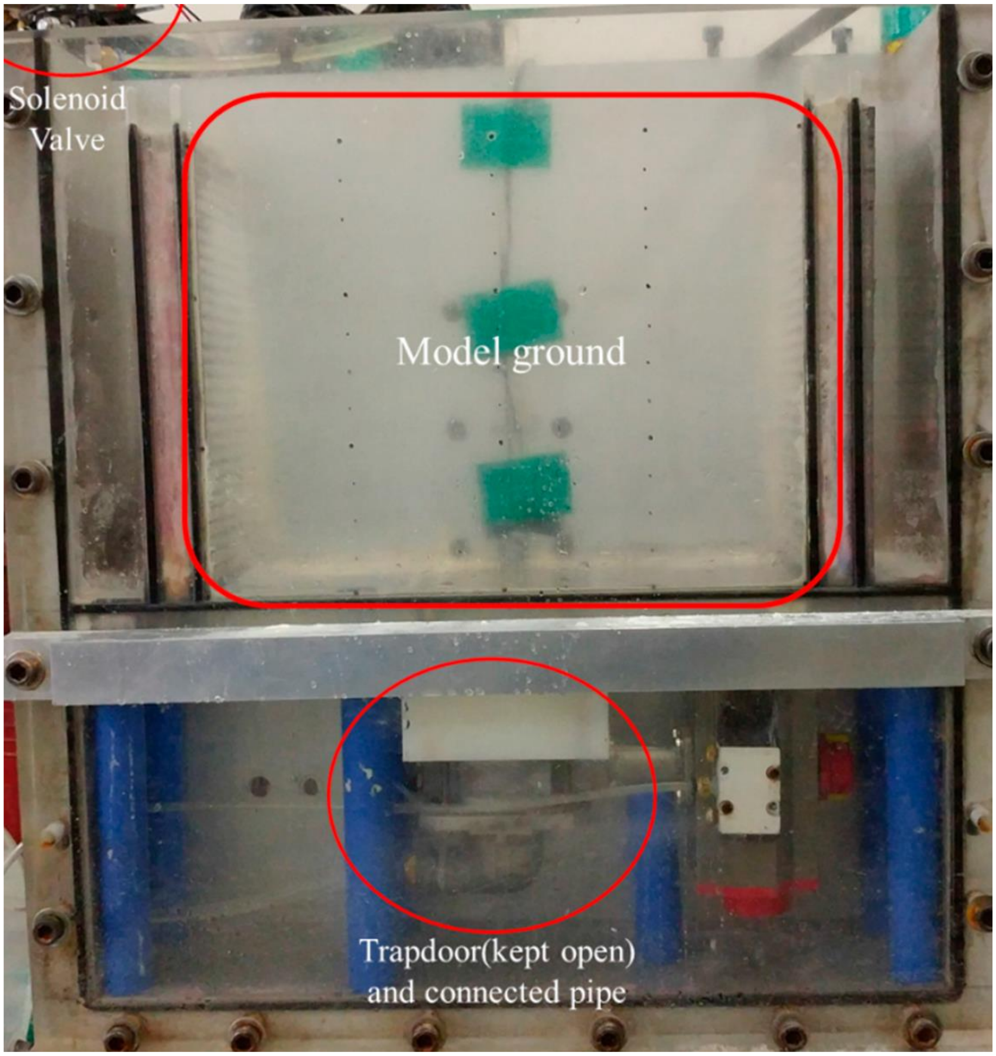


Figure 2-10 Front view of the test set-up (Karoui 2018)

Zhang et al., 2018, used gap grading soil samples and performed number of model experiments to explore the mechanism of internal erosion leading to cavity formation. basic concept of tests is to irritate the seepage erosion through the pipeline defect. Their results demonstrated that the cavity and the erosion area in the unsaturated soil was less expanded than in the saturated soil. Also, the defect direction has no effect on erosion process. In addition, higher hydraulic head increases the erosion region and cavities at the water table.

### 2.5.3 Soil erosion induced by water exfiltration

Van Zyl et al., 2013, performed a number of laboratory tests to study soil fluidization due to defective pipes. The inlet water flow rate was controlled to monitor soil fluidization zone and the head loss Fig. (2-11). Based on the analysis of the results, they found that the size of the orifice has no significant impact on the fluidized zone, and the water head is largely consumed within the fluidized zone.

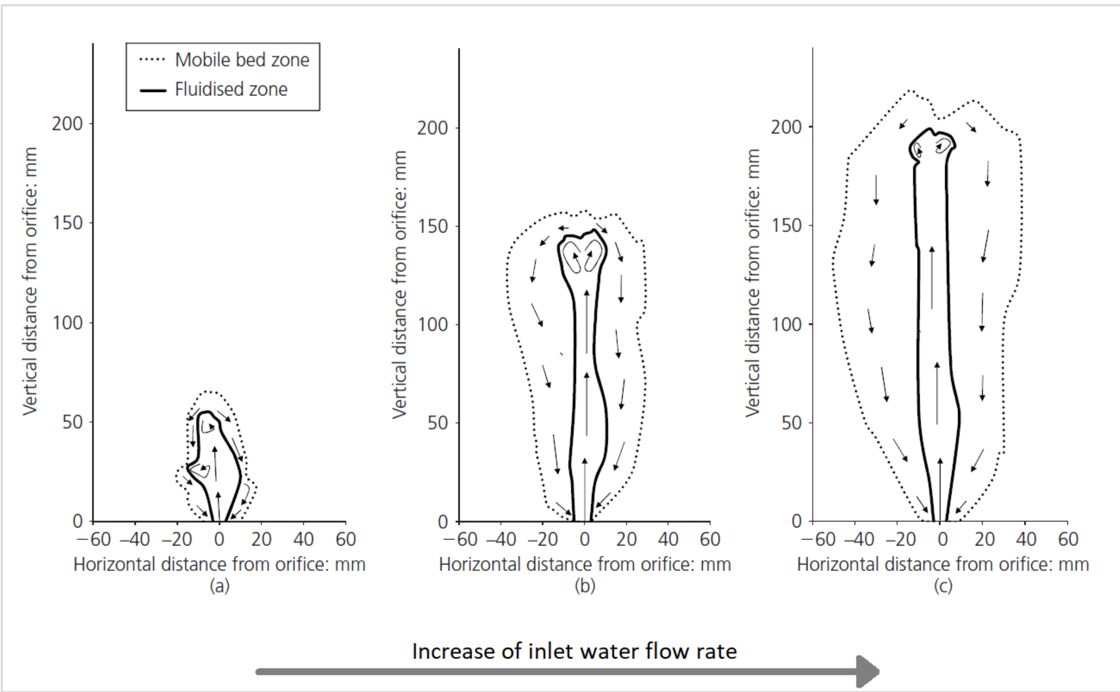


Figure 2-11 Shape of the fluidized zone as increase water flow rate (Van Zyl et al., 2013).

The mechanism of granular fluidization around defective pipes was investigated by (Alsaydalani and Clayton, 2014) who conducted laboratory experiments using similar model as van Zyl et al. (2013). They found that the soil transformed into a fluid like state at failure. When the pressure inside the pipe reaches a certain value, the upward water seepage force would be equilibrate the buoyant weight of the soil. Then, fluidization zone would be enlarged to the surface due to loosened soil particles. Similarly, (Alsaydalani and Clayton, 2014) suggested a prediction model to estimate the beginning of sand bed fluidization by an upward water jet Fig. (2-12).

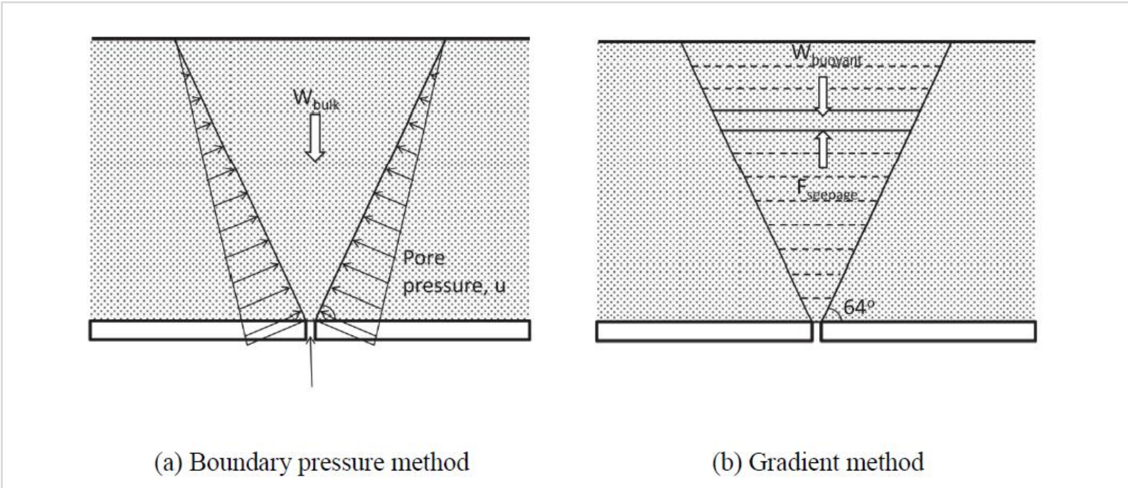


Figure 2-12 Model predicts the beginning of fluidization over an upward orifice (Alsaydalani and clayton, 2014)

Cui et al., 2012 presented a two dimensional numerical model based on discrete element method (DEM) and lattice Boltzmann method (LBM) to simulate the defective pipe buried in a granular soil . The fluid phase was simulated using LBM. While, granular material was described using DEM. From their examination Fig. (2-13), at the beginning, the cavity was formed by the effect of washing induced by the water stream, then it followed by a stable stage where the cavity remains without any enlargement even if the velocity of the water jet has increased. The final stage, is the collapse of the whole granular soil. (Cui et al., 2013, 2014) used the same numerical scheme as (Cui et al., 2012) to study the impacts of parameters on the formation and development of cavity by the upward water stream. They found that particle bonding can raise the granular soil resistance against the cavity growth. Height of soil can limit the growth speed of the cavity unaccompanied by the changing of the eventual form of the cavity.

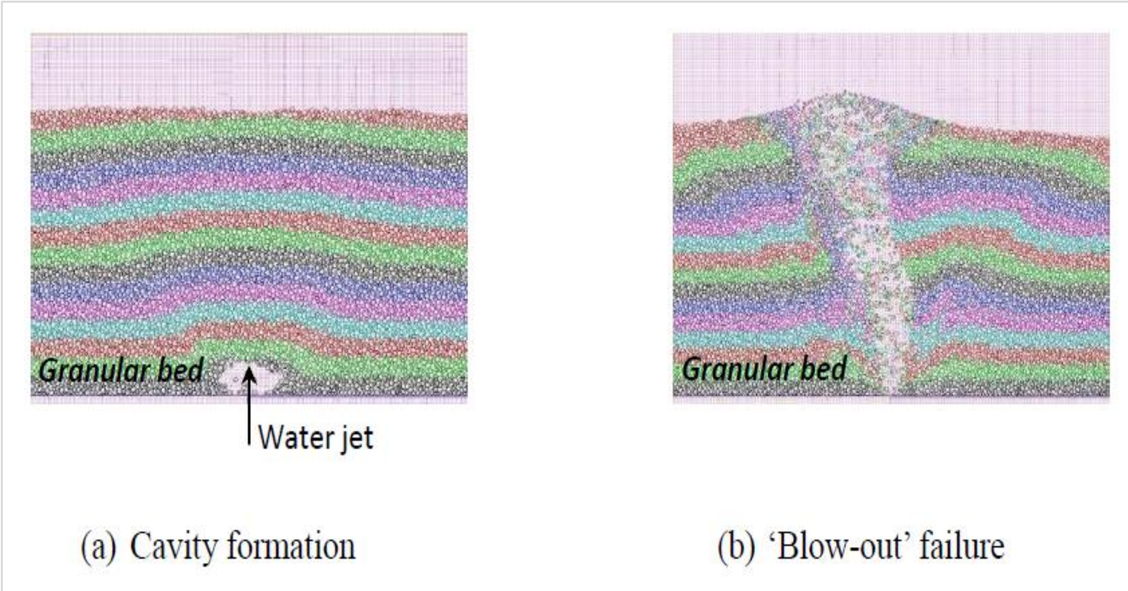


Figure 2-13 The Stages of cavity formation (Cui et al., 2012)

He et al., 2017, studied the erosion of soil by an upward water jet through a pipe defect using an experimental model. Fig. (2-14) shows the different stages of erosion, which were identified by the analysis of the results. Also, they were comparable to the numerical emulations by (Cui et al., 2012, 2014). Where the cavity is formed and enlarged with the increasing of water flow rate through the defect, and then the soil becomes fluidized at the flow rate which is called the critical flow rate. Similarly, (He et al., 2017) proposed a simple analytical model to predict the critical flow rate that caused soil fluidization depending on the force equilibrium and Darcy's law.

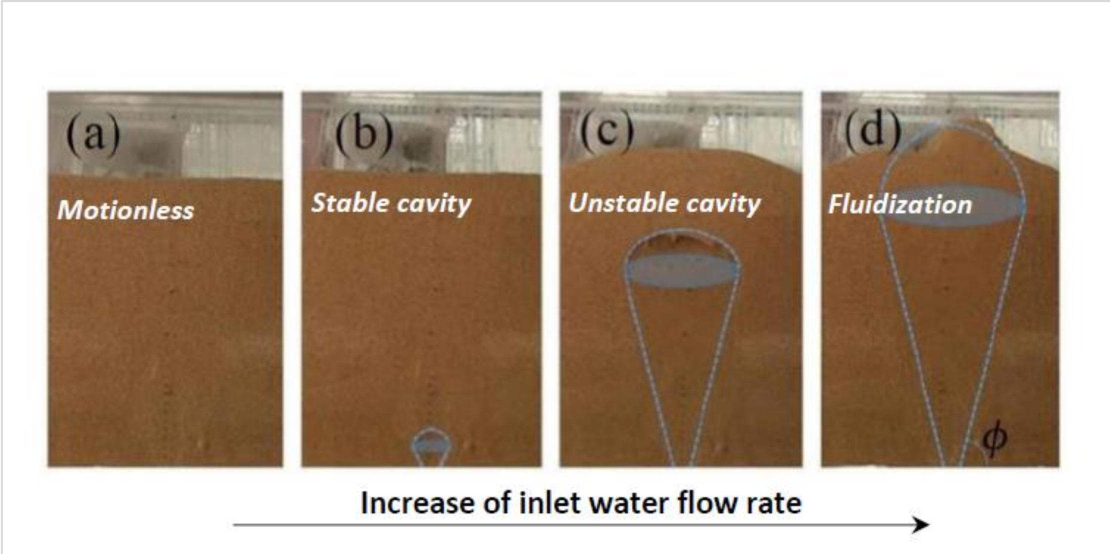


Figure 2-14 Soil erosion phases by upward water stream (He et al., 2017).

Fluidization of granular soils induced by fluid stream was examined by other researchers in chemical engineering to improve chemical reactions (Benyahia et al., 2000; Chen et al., 2011; Cooper and Coronella, 2005; Taghipour et al., 2005). Where it was found that the granular particles will be restructured and the inside arrangement of the soil particles medium is adjusted due to the generated force by fluid flow inside the immersed granular soil. Different systems of fluidization were identified with the increasing of fluid entry flow rate (Nermoen et al., 2010; Philippe and Badiane, 2013; Rigord et al., 2005; Zoueshtiagh and Merlen, 2007).

Chen et al., 2011, studied fluidization of granular soils and found that the movement of soil particles was influenced by the velocity of the fluid and they pointed to the smallest velocity that cause fluidization the critical velocity .

## 2.6 Review of Previous Apparatuses For Soil Erosion Induced Defective Pipes

Several researchers studied the process of soil migration through defective sewer pipes using experimental model tests (Rogers 1986; Kuwano et al. 2006; Mukunoki et al. 2009; Sato and Kuwano 2010; Guo et al. 2013). The capabilities and characteristics of these previous apparatuses are reviewed and discussed in this section.

It is very necessary to control the leakage width in the experimental apparatus, because it is importante in determining the the critical leakage width. Rogers (1986), investigated the rate of soil loss by using two apparatuses (small and large). In the small apparatus and during the water infiltration test, the leakage width was increased progressively until the beginning of the soil erosion. While, in true situation the leak width changes very slowly and it is almost constant in short time periods. Therefore, the results might be inaccurate. As for the large apparatus, a real defective pipe was used buried in the soil. Nevertheless, changing the defective pipe each time when performing the experimental tests with different leakage sizes and soil types is very difficult and not practical. (Mukunoki et al. 2006; Mukunoki et al. 2009; Mukunoki et al. 2012), they concluded that leakage width is very important because it determines the area of soil exposed to the erosion as well as the size of soil granules that can enter the sewer pipe Fig.(2-15). Also they found that the leakage orientation was unimportant.

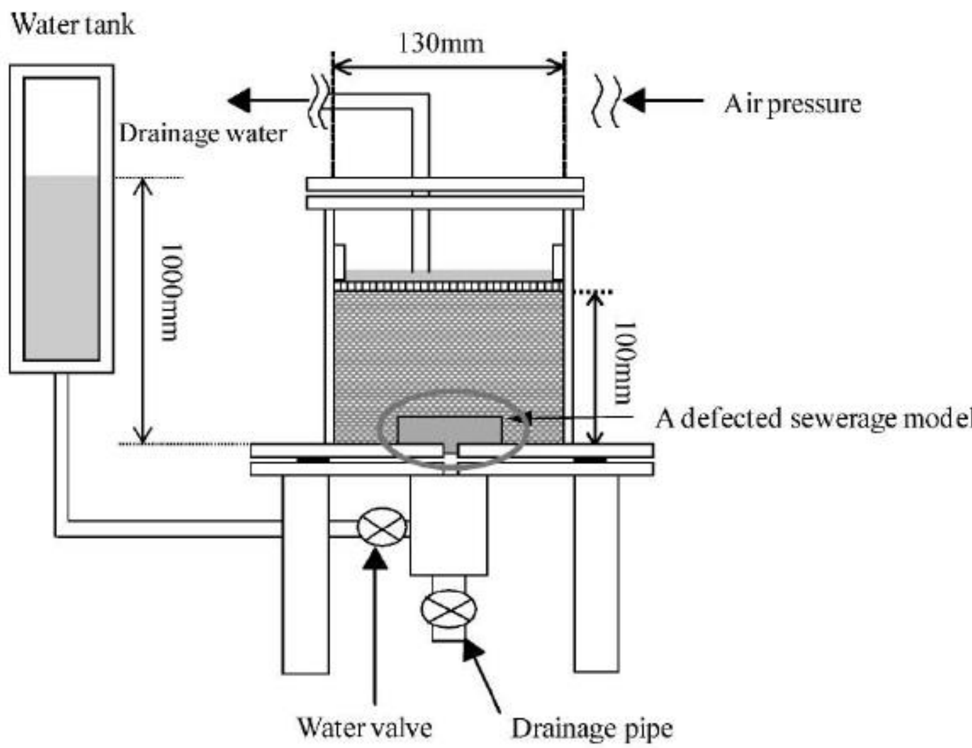


Figure 2-15 illustration of the test apparatus (Mukunoki et al. 2006)

Other test approaches tested the effect of sewer depth which is important factor because it can affect the scale of erosion and also increases the possibility of sewer pipe deterioration and the appearance of defects (O'Reilly et al., 1989). Depending on the type of the sewer pipe and the situation of the ground, the authorities often specify the minimum and maximum cover depth required over the sewer pipe (e.g. (United States Department of the Interior, 1996)).

The surcharge load in the previously mentioned methods was controlled by using water (Rogers 1986; Guo et al. 2013) Fig.(2-16), or by compressed air (Mukunoki et al. 2006; Mukunoki et al. 2009; Mukunoki et al. 2012; Ke and Takahashi, 2014), or by surcharge weights (Sato and Kuwano 2008; Renuka and Kuwano 2011; Sato and Kuwano 2013). Test methods often conducted using single leakage, which is either circular opening (Guo et al. 2013) Fig.(2-17), or rectangular in shape (Mukunoki et al. 2006; Sato and Kuwano 2008; Renuka and Kuwano 2011; Kuwano et al. 2012; Sato and Kuwano 2013).

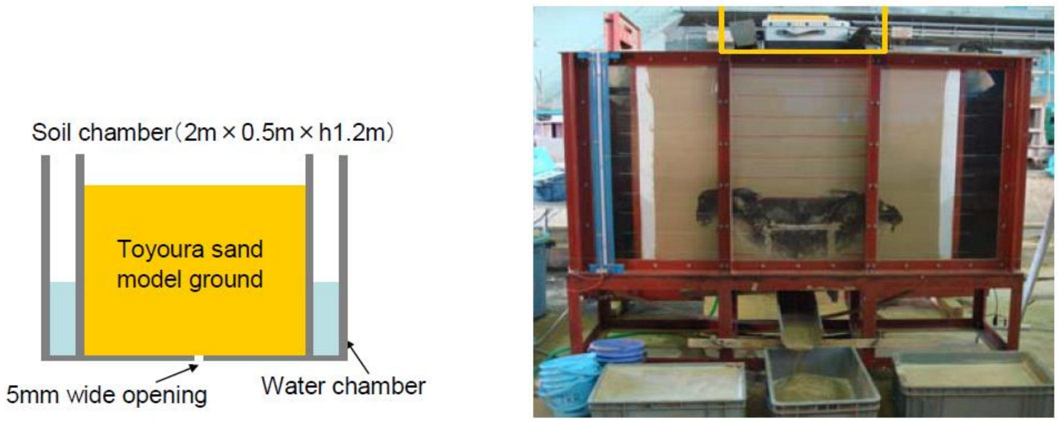


Figure 2-16 Illustration of the test apparatus (guo 2012)

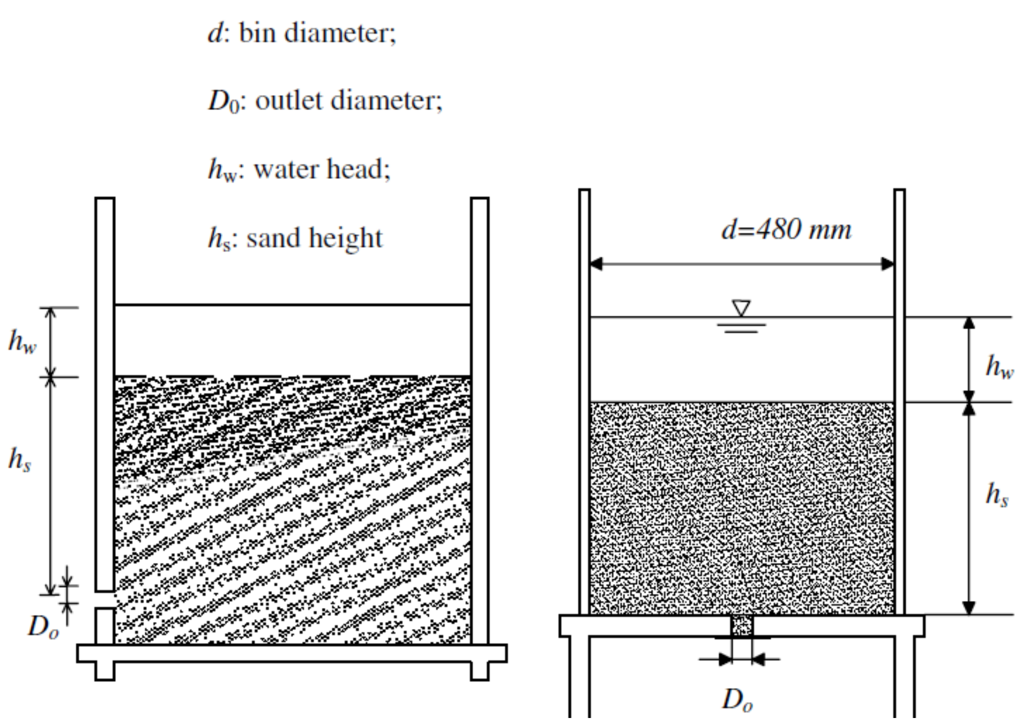


Figure 2-17 Illustration of the test apparatus (guo 2013)

Soil erosion and migration into defective sewer pipes are occuring due to either water infiltration, exfiltration or due to cyclic flow behavior. therefore, controlling water seepage is necessary to simulate properley the process of soil erosion inside the apparatus. Majority of previously mentioned methods are conducted using continuous water flow infiltration or exfiltration through the pipe defect (Rogers 1986; Mukunoki et al. 2006; Mukunoki et al. 2007; Sato and Kuwano 2008; Mukunoki et al. 2009; Renuka and Kuwano 2011; Mukunoki et al. 2012; Sato and Kuwano 2013). Aside from the direction of water seepage, it is necessary to control the water flow rate during the test to keep up a similar hydraulic condition in the soil and to precisely anticipate the volume of water. Some of the previous studies utilized a fixed volume of water either per test or per cycle, howerver other studies utilized a fixed water head tank to accomplish a consistent water flow rate all through the test. There is a problem that can occur using the fixed water head tank, the issue is the flow of air with the water into the model when full flow isn't kept up in the supply pipes (Kenney and Lau, 1986). Wherefore, maintaining full flow in the supply pipes is necessary to limit the disturbing influence of the air. The majority of the previously apparatuses were intended to gather the eroded soil by a box form gadgets that are attached to the pipe defect. Where the eroded soil particles can stack simply and obstruct at the level base of the box resulting in incorrect quantification of the eroded soil. To conquer this problem, (Indraratna et al., 1996), utilized a conical base gadget which helped to increase the accuracy of the results. Monitoring the settlement of soil surface due to soil erosion is essential, in order to sense the effect of soil movement, which resulting from the erosion process on structures. One way in which soil descent can be observed by using sensors. However, using sensors in the model ground can disarrange soil movement behavior, as the sensors have a strengthening impact on the soil (Ng et al., 2002). Furthermore, it is difficult to obtain detailed displacement profile for the model ground, because it means using more sensors which increase the unsettling influence considerably and make it more prominent. Therefore, monitoring the ground displacement require a viable and feasible way which allows the observation of different layers of the model ground.

From this review of soil erosion test apparatuses. The important and necessary features are required for functional and practical erosion test model can be recognized. The adopted apparatus ought to be capable of:

1- Controlling the leakage width, water flow rate and loads.
2- Observing the movements of soil layers in the model ground.
3- Identifying the amount of eroded soil and their properties
4- Observing the cavity formation and propagation.
5- Feasible and easy to use with less boundary effects

Taking into account all the above mentioned features, an economic, appropriate, practical apparatus was designed, as described in chapter four.

## 2.7 summary

The literature review conducted above related to the soil erosion induced by defective sewer pipes revealed that, the mechanisms of soil erosion process is still not clear and need further studies. Where a number of previous studies dealt with the subject of soil erosion under the influence of water infiltration or exfiltration and the factors affecting the process. While, erosion due to cyclic flow has received less attention compared to its importance. In addition, the previous studies did not give a clear weight and comparison of the impact of factors affecting the process of erosion. The current study adopted the cyclic flow to study the erosion of the local sandy soil under a different matrix of the influencing variables, in order to study the extent of its impact as well as to build a model that estimates the rate of erosion.

# Chapter Three

## Dimensional analysis

## 3.1 introduction

This chapter presents a general overview on the dimensional analysis and the methodology of the dimensional analysis for the present study.

## 3.2 Dimensional analysis background

Dimensional analysis is a mathematical tool that shapes the general form of relations that describe natural phenomena. Dimensional analysis can be applied to any physical phenomenon by assuming that the phenomenon can be represented by several variables (V) (V1, V2,…, Vl), including a total of m independent primary dimensions (D) = (D1, D2,…, Dm) (e.g. mass, length, time), where these are the minimum number of dimensions needed to define all the variables. Variables are divided into dependent variables like (bending moments, stresses) and independent variables such as (mass, size, density) (Butterfield, 1999).

Through the using of dimensional analysis, the space needed to describe and analyze certain physical phenomena can be reduced by integrating variables into dimensionless groups, where the number of resulting groups is less than the number of variables. In general, Buckingham's theorem (Buckingham, 1914) revealed that an original equation including l variables and m dimensions can be decreased to a dimensionless relationship including only N dimensionless parameters, where:

1- $N = l - m$

The resulting N dimensionless parameters are conventionally labelled as (p1, p2,…, pN) (i.e. Pi groups). As each p is dimensionless, the final function must be dimensionless and therefore dimensionally:

2- $f(p1, p2,\ldots, pN) = M^{0}L^{0}T^{0}$

The form of function *f* is not delivered by the dimensional analysis, but it is usually approached by an experimental, dimensionless equation fitted to either model or prototype data. Furthermore, the Buckingham theorem does not offer any particular regulation concerning to the selection of variables, which appear in each Pi group used for the reduction of the problem. In order to enable systematic computation of dimensionless numbers, input and output variables of a concept are considered as performance variables. Choice of repeating variables should be done within the concept's internal variables and according to the unique number of the system's governing dimensions for best results (Christophea et al., 2008).

## 3.3 Dimensional analysis methodology

Dimensional analysis was utilized as a tool in the present study, for suggesting a dimensionless model to predict the soil erosion of local experimental soil, due to water exfiltration/infiltration cycle through defective sewer pipe. Cyclic water flow and soil drainage throght sewer pipe defect could lead to fatal failure in the soil and roads near the defected sewer pipe and this could endanger lives and property. Several researchers studied soil erosion caused by cyclic water flow. Several parameters have been recognized as potentially important (as reviewed in the previous chapter). In the present study, cyclic water exfiltration/infiltration case was adopted, where a typical way of soil erosion to happen is when the stormwater and the sewage water are filling the sewers, and may exfiltrate from the sewer pipe through the defects, which cause disturbing the surrounding soil and leads to the fluidization of it Fig(3-1a) . When the rain ends, the level of groundwater decreases, accompanied by the migration of the irritated soil granules into the sewer pipe through the pipe defects, the repetition of this process leads to the creation of the cavity, the ground cavity gradually expands and eventually a sinkhole Fig (3-1b).

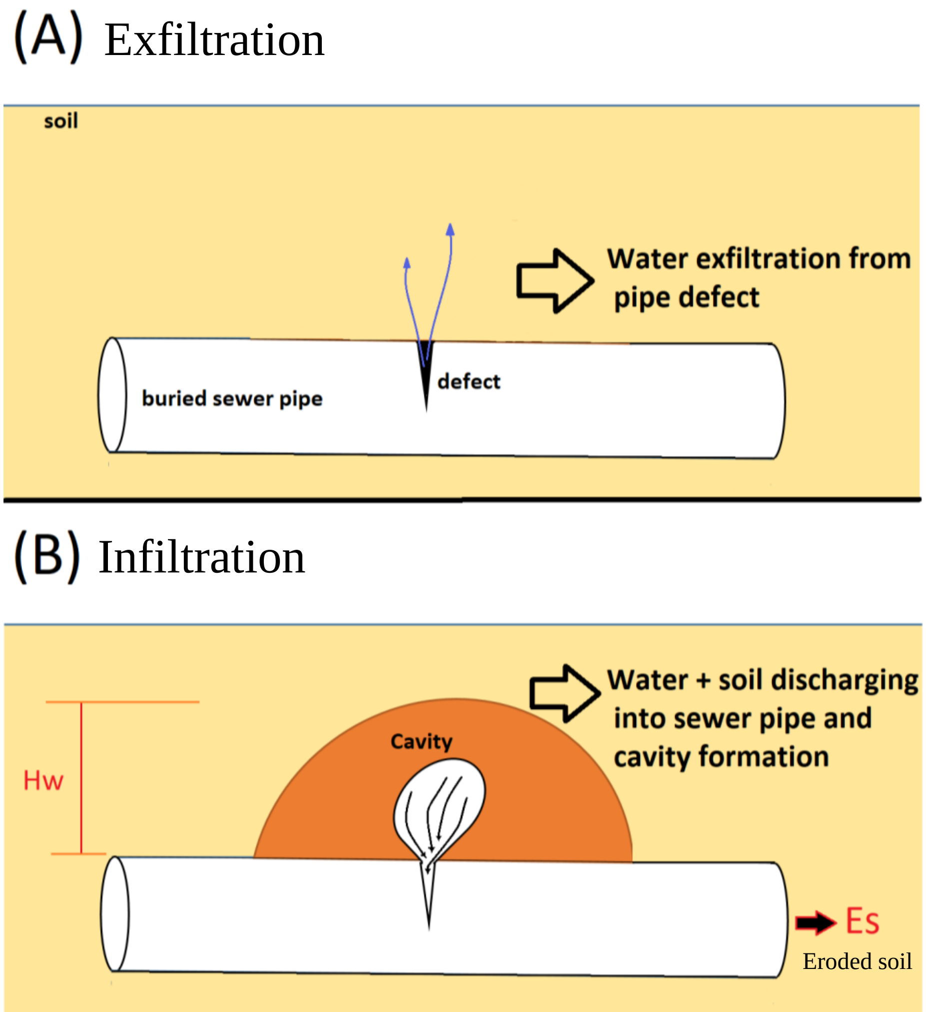


Figure 3-1 typical way of soil erosion due to cyclic flow through pipe defect

The present study explored the mechanism of soil erosion by water exfiltration/infiltration cycle through pipe defect and using dimensional analysis to develope a dimentionless model that predicts the soil erosion of local soil. The application of dimensional analysis accounts for most of the factors influencing the erosion process. In the present study, leakage width, particle size distribution, dry density of the soil, initial water content, the height of water level in soil, the flow rate through the leakage and the number of cycle , assumed to be primary factors Table (3-1).

Table 3-1 factors that influence the process of soil erosion

| factors | Abbreviation | units | Basic dimension |
|---|---|---|---|
| Leak width | B | mm | [L] |
| Particle size distribution | $D_{70}$ | mm | [L] |
| Dry density of the soil | ρ | $Kg/m^3$ | $[M].[L]^{-3}$ |
| water flow rate through the leak | Q | ml/sec | $[L]^3\ [T]^{-1}$ |
| Initial water content | W | - | $[M]^0\ [L]^0\ [T]^0$ |
| Number of cycle | C | - | $[M]^0\ [L]^0\ [T]^0$ |
| Height of water level above the defect in soil | Hw | cm | [L] |
| Acceleration | g | $m/sec^2$ | $[L].[T]^{-2}$ |

The total amount of eroded soil (Es)( the total amount of soil that discharges with water into sewer pipe through defects) is the depended variable, which depend on the previously mensioned factors and can be represented using the list of these parameters, as shown in Equation (3-1)

$$Es = f(\rho, B, Q, W, Hw, C, D70, g) \quad \text{………..} \quad (3\text{-}1)$$

Equation (3-1) involves nine variables and three dimensions (mass, length and time). According to Buckingham's Pi theorem (Buckingham 1914). Number of dimensionless variables required to describe the problem equals the number of dimensional variables, nine as indicated by Equation (3-1) minus the number of primary dimensions required to describe the problem. Depending on the way that the presented variables are merged, equation (3-1) can be reduced to a simple equation including six dimensionless parameters. For a group of variables appearing in each dimensionless parameter. They have to be combined in such a way that the powers of each 'dimensions' appearing in the group are separately equal to zero. A number of groupings is possible to form dimensionless parameters. Yet, the correct groups of dimensionless parameters are required to be selected and have to be proved by the experimental data.

The six dimensionless groups are generated by choosing three repeating variables and grouping them with one of the remaining parameters, forcing the product to be dimensionless. In this way, all the dimensionless groups can be constructed.

For $\boldsymbol{\pi_1}$ (which is the first dimensionless group)

$$1 = ( \rho^a \; D_{70}^b \; Q^c \; Es ) \quad \ldots\ldots\ldots\ldots (3\text{-}2)$$

where **ρ**, $\mathbf{D_{70}}$ and **Q** are repeating variables

**Es** is the depended variable

By substituting the basic dimensions in the previous equation we have :

$1^0 = M^a L^{-3a} \times L^b \times L^{3c} T^{-c} \times M^1$

| | | |
|---|---|---|
| M | a + 1 = 0 | a = -1 |
| L | -3a + b + 3c = 0 | b = -3 |
| T | c = 0 | |

And therefore $\pi_1 = \frac{Es}{\rho\ (D70)^3}$

By following the same method for the five remaining independed variables, the dimensionless equation takes the following form:

$$\frac{Es}{\rho\ D70^3} = f(C,\ W,\ \frac{B}{D70}\ ,\ \frac{Hw}{D70}\ ,\ \frac{g\ D70^5}{Q^2}\ ) \quad \ldots\ldots\ldots.. \quad (3\text{-}3)$$

Where:

Es/(ρ (D70)^3 ): (The Rate of Erosion) : It is a parameter that represents the total accumulated eroded soil relative to the physical quality of sandy soils (particle size and dry density).

C: (Number of Cycle): Represents the sequence of the cycle in the periodic flow.

W%: (Initial Water Content): It is the amount of primary water content of the soil at the beginning of the periodic flow.

B/D70: (Leakage Width Ratio): This term represents the ratio between the size of leakage and the size of soil granules, which is one of the most important factors affecting the process of erosion. The larger the leakage and the smaller the size of the soil granules, the greater the possibility and ease of movement of the soil into the pipe through the leakage.

Hw/D70: (Water Height Ratio): This parameter represents the ratio of water height in the soil to the size of soil granules. Where it gives an indication of the hydraulic state of the soil. The increase and ease of the spread of water in the soil leads to an increase in the amounts of soil transferred to the inside of the sewer pipe.

(g (D70)^5)/Q^2): (waterflow discharge factor): This coefficient represents the ratio between the size of soil granules and the amount of waterflow discharge and its effect on soil erosion. The amount and speed of waterflow play an important role in soil erosion due to the continuous flow of water.

Having defined the dimensionless groups , it become necessary to determine the correlation between them in order to establish which dimensionless charts correlated to the best in terms of behavior, to facilitate the interpretation of the experimental work data.

A testing apparatus is built to simulate the process of soil erosion due to cyclic water flow through sewer pipe defect, it is designed to facilitate the change of the influencing parameters for both dimensional analysis and soil erosion investigation Fig (3-2). The proposed apparatus, its parts, details and way of operation are described in the next chapter.

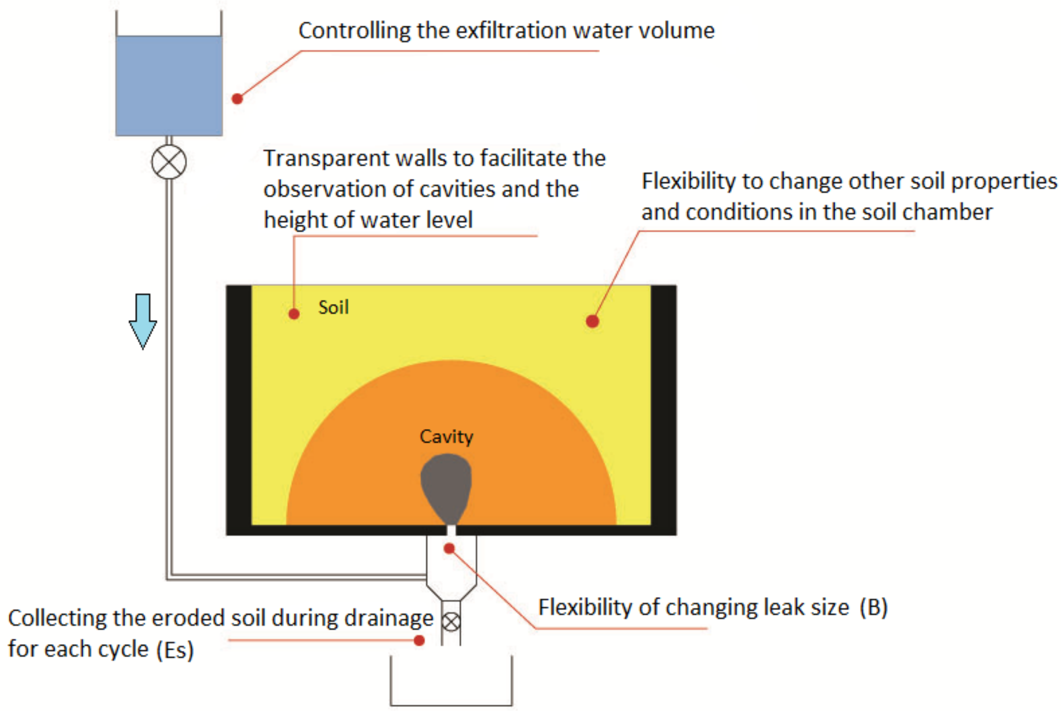


Figure 3-2 Schematic diagram of experimental setup and key features that facilitate the dimensional analysis

Experimental tests simulating cyclic water through sewer pipe leakage was performed under varying matrix of influencing parameters. This simulation for applying the dimensional analysis and for evaluating the erosion of local soil in all different conditions combination. The method and details of the experimental work, and the matrix of influencing parameters are described in the next chapter of experimental work. While, interpretation of the experimental data, the effect of each one of the dimensionless groups, the correlation between them and the proposed dimensionless model is presented in chapter five (Results And Discussions).

## 3.4 Statistical Analysis Model

The statistical analysis was used to develop the model which, connects between dependent variables and independent variables. The aim of this section of the present study is to illustrate sufficient knowledge of how parameters affects to the depended variable. In the present study it was decided to use Statistical Product and Service Solutions (IBM, SPSS) software (Version 24). Experimental tests are conducted with varying matrix of influencing parameters such as , leakage with , particle size distribution, dry density of the soil, initial water content, height of water level in soil, flow rate through the leakage and the number of cycle, which represent independent variables, while total eroded soil represents the dependent variable.

Analysis of linear and nonlinear regression were conducted to find the most valid statistical models. Predictive modeling is a name given to a collection of mathematical techniques having in common the goal of finding a mathematical relationship between a target dependent variable and various predictors or independent variables, with the goal in mind of measuring future values of those predictors and inserting them into the mathematical relationship to predict future values of the target variable. Perfect in practice, it is desirable to give some measurements of uncertainty for the predictions; typically a prediction interval that has some assigned level of confidence like 95%. Another task in the process is model building. Model selection, fitting and validation are the basic steps of the model building process.

# Chapter Four

## Experimental Work

## 4.1 Introduction

This chapter deals with experimental work which was conducted during interval of the present study. It presents: the used materials, the proposed apparatus and the adopted testing methods.

## 4.2 Materials

Local materials were used in the present study are:

### 4.2.1 Sandy soil

Local sandy soil was used in this study. Soil is provided from local materials in Karbala governorate, more specifically from Al-Hur area. Soil samples were sieved, according to ((ASTM, 2007), ASTM D 422 standard test method for particle size analysis of soils). The gradation is shown in Fig. (4-1). Other specifications  is shown in Table 4-1. It is classified as a poorly graded sandy soil according to the unified soil classification system (ASTM D 2487 - 17).

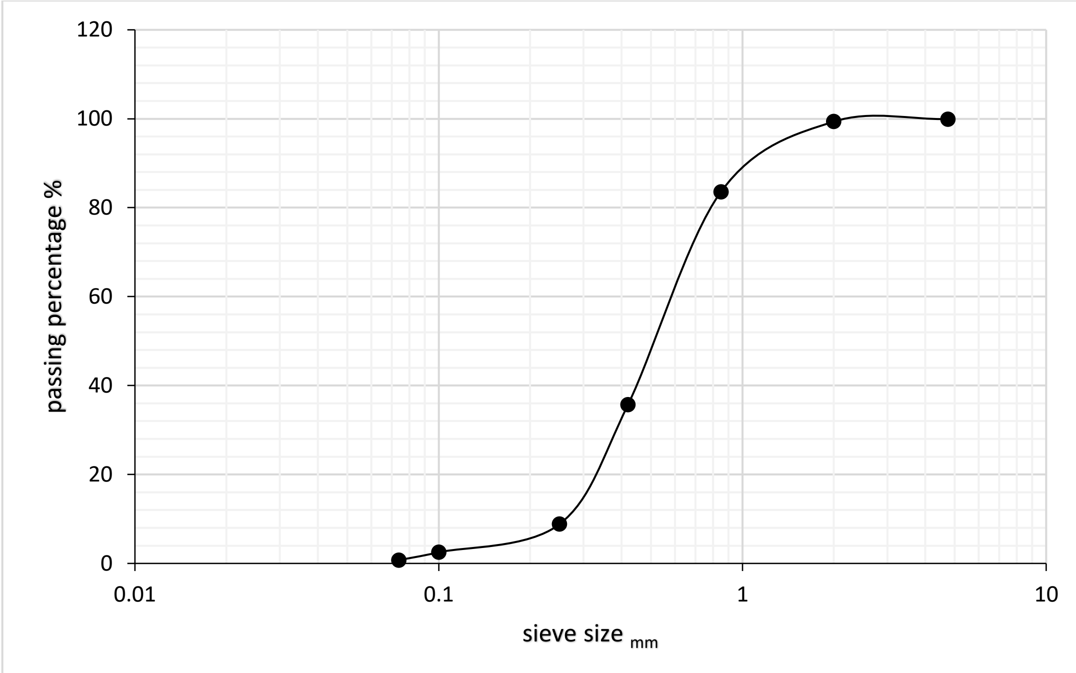


Figure 4-1 Particle size distribution of exprimental sandy soil

Table 4-1 Exprimental sandy soil properties

| Property | ASTM Designation | Value |
|---|---|---|
| Specific gravity | ASTM D854-14 | 2.65 |
| Coefficient of Gradation<br>$Cc = D_{30}^2/D_{60}\ D_{10}$ | ASTM D2487-11 | 1 |
| Coefficient of Uniformity<br>$Cu = D_{60}/D_{10}$ | ASTM D2487-11 | 2.28 |
| $D_{70}$ | - | 0.85 mm |
| Optimum water content | - | 9% |

### 4.2.2 Sewer pipe embedment material

Subbase was used in the present study as sewer pipe embedment material. Type (D) was used according to Iraqi specifications (The State Corporation for Roads and Bridges, 2003). Subbase type (D) was characterized by its small granular gradients compared to the A, B and C types as shown in Table 4-2. The gradiation and other properties of the experimental subbase is shown in Fig. (4-2) and Table 4-3 .

Table 4-2 Granular Material – Grade Requirements ,(The State Corporation for Roads and Bridges, 2003)

| US Sieve Size | | Type A | Type B | Type C | Type D |
|---|---|---|---|---|---|
| Mm | Alternative | | | | |
| 75 | 3 in | 100 | | | |
| 50 .0 | 2 in | 95-100 | 100 | | |
| 25,0 | 1 in | | 75-95 | 100 | 100 |
| 9.5 | 3/8 in | 30-65 | 40-75 | 50-85 | 60-100 |
| 4.75 | No.4 | 25-55 | 30-60 | 35-65 | 50-85 |
| 2.36 | No.8 | 16-42 | 21-47 | 26-52 | 42-72 |
| 0.30 | No.50 | 7-18 | 14-28 | 14-28 | 23-42 |
| 0.075 | No.200 | 2-8 | 5-15 | 5-15 | 5-20 |

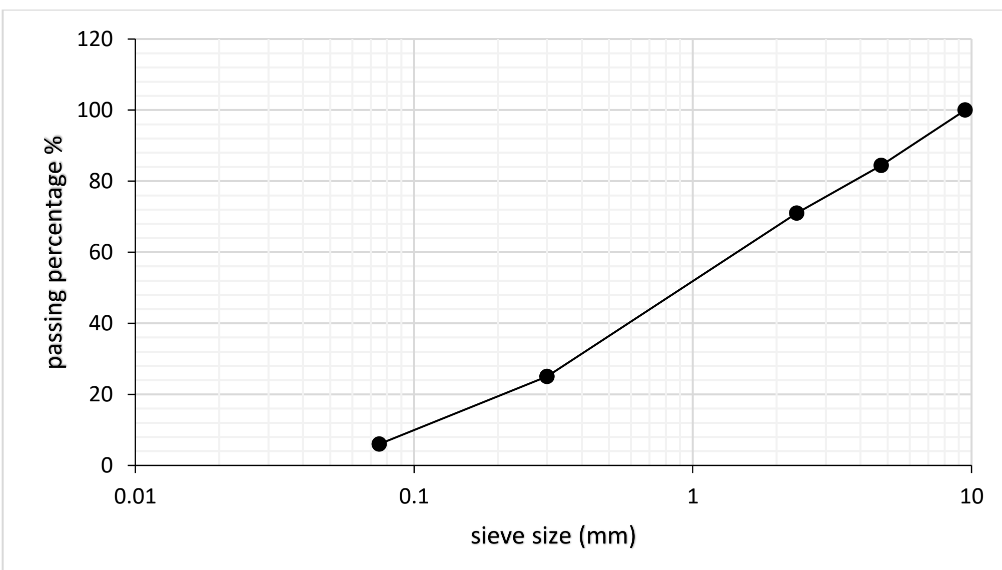


Figure 4-2 Particle size distribution of  exprimental subbase type (D)

Table 4-3 Experimental subbase properties

| Property | Value |
|---|---|
| $D_{70}$ | 2.35 mm |
| Optimum water content | 8% |

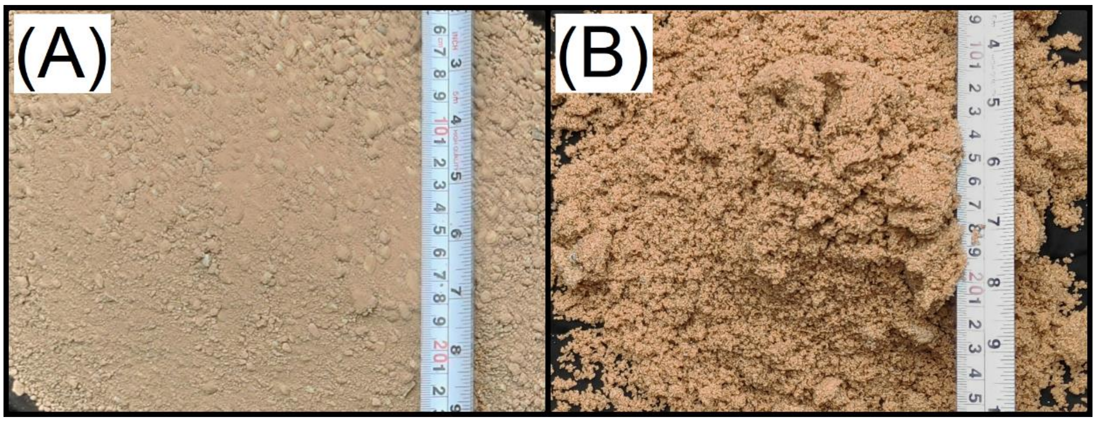


Figure 4-3 (A) subbase type (D), (B) sandy soil

## 4.3 Proposed Apparatus

the present study explores the process of soil erosion, and investigates the susceptibility of soils to erosion, and the corresponding ground displacement due to defective sewer pipes utilizing experimental model that emulate the erosion process in real situation. Several of earlier devices were presented. Also, studied their strengths and weaknesses were identified, the adopted apparatus were designed to address the essential concerns related to these devices. Adopted apparatus is able to explore the process of soil erosion, and measure the amount of eroded soil in addition to observing the ground displacement near the defect as well as at the ground surface during the test stages. However, this approach is extremely viable for coarse grained soils. Schematic diagram and an image of the experimental model are shown in Fig. (4-4) and Fig. (4-5) respectively. The experimental model is made up of five fundamental parts:

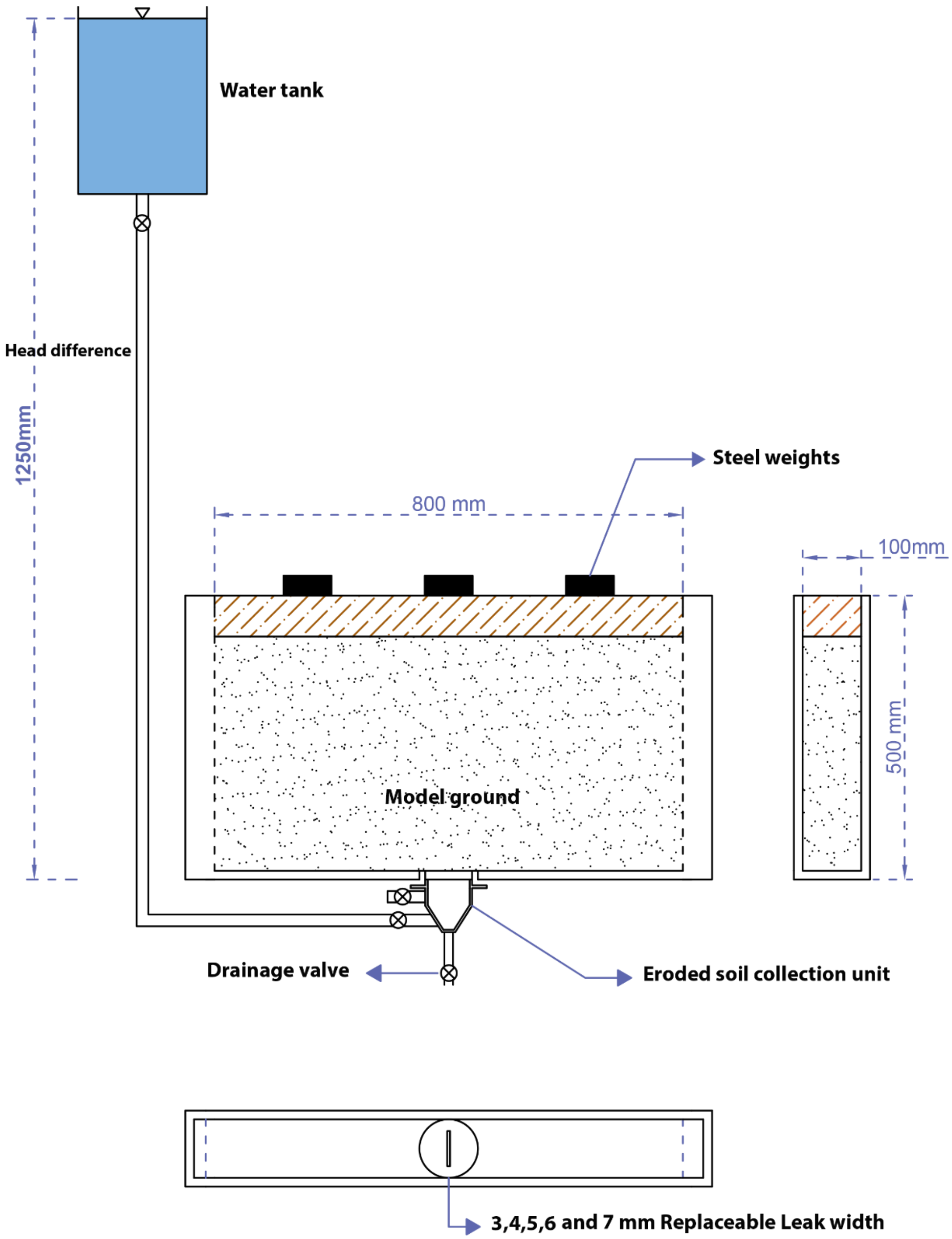


Figure 4-4 Schematic diagrams of experimental setup

1- Main soil chamber.
2- Two extra side chambers which allow water to move through to maintain steady boundary conditions.
3- Leakage width control and eroded soil collection unit.
4- Fixed head water tank and flow rate control unit.
5- Additional loads unit.

In order to overcome the disadvantages of small models and their boundary condition issues. The device was designed to be as large as possible and practical at the same time. The main soil chamber was designed to be 800 mm long, 500 mm high, and 100 mm wide. The front and back walls of the soil chamber have made from 10 mm tempered glass and the frame was made of steel. The transparent walls are used to allow monitoring of the soil movement and the cavity formation process from outside. Horizontal lines were sketched on both sides of the front and back walls at 50 mm spaces. This design helped in the control of the following soil layer thickness. In addition, two vertical lines were marked on the front wall in the middle of the model, which intersect with the horizontal lines forming squares of 50 mm by 50mm. This helped in the monitoring of the soil layers settlement above the leakage. Two extra chambers were located along each side of the main soil chamber, each one has 50 mm of length and isolated from the main soil chamber by a permeable wall. Permeable wall allows water to pass through into the side chambers, but prevent soil particles transmission. Therefore, a real situation of the ground can be more accurately simulated. Eroded soil collection unit was placed at the base of the soil chamber. It has 100 mm diameter and 100 mm height with conical shaped bottom. The surface of this unit then has the same level with the base of the soil chamber. This represents a defect at the crown of the pipe. More leakage sizes can be used by changing the eroded soil collection unit with those, which have a different leakage size. An O-ring was placed between the soil chamber base and the eroded soil collection unit. Advantage of O-ring is avoiding the leakage of water or soil through this connection. Eroded soil collection unit has a water inflow valve located on the side of the unit and a drainage plug located at the bottom of the unit. The drainage plug remains closed during the water inflow period and is opened at drainage.

Steel weights were placed on timber beams which placed on the soil surface to simulate the weight of backfill soil above the sewer pipe. Different sewer depths can be simulated by changing the amount of load. A constant head tank was used with a 4 mm diameter high stiff pipe from the tank to the water inflow valve. Water flow rate is fixed and measured by water volume with time.

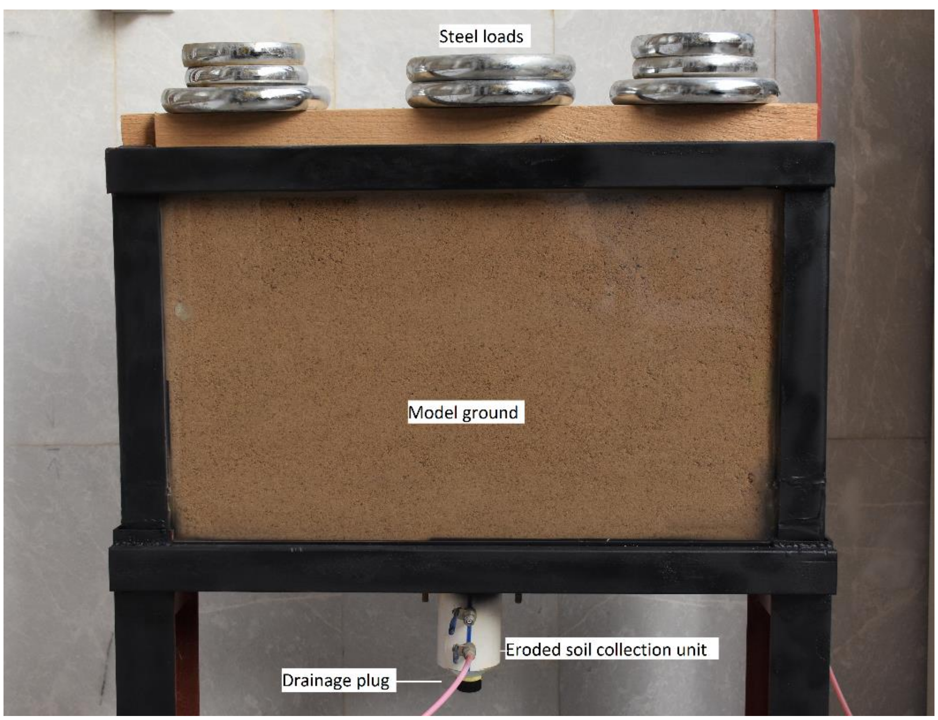


Figure 4-5 Image of experimental apparatus

## 4.4 Testing procedure

The present study is prepared to simulate the cyclic water flow through pipe defects. Where, water flow out of a sewer into the soil, after that returns once more into the sewer through the pipe defects. this process can occur as a result of the temporary changes in the flow inside the sewer pipes. As a first step to prepare the apparatus to perform tests, the eroded soil collection unit with the desired leakage width was placed at the bottom of the soil chamber and connected with screws. Consequently, surface of the unit is then at the same level with the base plate of soil chamber and the leakage length is perpendicular to the glass walls.

To prevent the soil particles from leaking out through the defect while filling the soil chamber, icing sugar was placed in the eroded soil collection unit. This substance dissolves when water flows into the soil chamber. Then, soil was added to the soil chamber in the form of layers. Each layer is 50 mm deep and compacted to the desired value of relative density. The sketched horizontal lines were used to control the thickness of each layer accurately. Steel weights were then placed on the timber beam that was placed on the soil surface to simulate one meter of soil depth above the sewer pipe. The model ground was left for 12 hours to reduce the potential creep effect. In such experimental work, the friction between the soil and the surrounding walls can has a bad effect on test results. Therefore, it should be removed or significantly reduced (Brachman et al., 2000, 2001; Tognon et al., 1999). In the present study, because of friction between glass and sand is believed to be insignificant, the friction effect was deemed to be negligible. Where, (Liu et al., 2011), stated that the friction angle is 14$^{o}$ for coarse sand on glass. According to this value, the maximum friction produced at the bottom of the wall has a value of around 5% of the total soil pressure, assuming a Poisson's ratio of 0.3 previously determined for sand backfill in a laboratory model test (Brachman et al. 2001). Furthermore, the existence of water will reduce the friction even under 5%. In addition, previous studies with similar laboratory model tests were deemed the friction between the sand and the glass walls insignificant (Tsutsumi et al., 2010; Guo et al. 2013; Sato and Kuwano 2015a).

For the present study, experimental model was intended to simulate a ground with a defective sewer pipe containing a 3,4,5,6 and 7 mm wide, 60 mm long leakage in the crown of the pipe. Water is supplied to the model ground through the leakage as a cyclic flow condition. where the water was moved across the leakage to the ground and then back to the pipe again causing soil erosion. The volume of the supplied water was controlled by time, and the initial rate of water flow was set to be 10 ml/s. At the point when the proper volume of water has crossed into the model ground, the drainage valve was shut and the model ground was left for 2 minutes to settle down the water level. After 2 minutes, the drainage plug was opened to let water and eroded soil flow out. A small valve close to the leakage was slowly opened during the drainage process to release the pressure and avoid the accelerated soil loss due to suction. This process of water supply/drainage is called a cycle and is repeated 10 times for each run. For each cycle, dry weight of the eroded soil was measured and then sieved.

The test procedure can be summarized by the following simple steps:

1- Choosing the desired leakage width.
2- Filling the soil chamber with soil and copacting it into layers.

3- Leaving the model ground for 12 to 15 hours to remove any creep effect.
4- Supplying the model ground with the desired water inflow volume through the leakage.
5- leaving the model for 2 minutes to stabilize the water level.
6- Opening the drainage plug to let the water and the eroded soil to drain out of the leakage.
7- Collecting, then drying, weighing and sieving the eroded soil.

Test conditions were changed to study the effects of the governing variables and to perform dimensional analysis technique, as shown in the Table 4-4 .

Table 4-4 Experimental tests variables

| Experimental tests variables | Values |
|---|---|
| Leakage width | 3, 4, 5, 6 and 7 mm |
| Water inflow volume | 0.25, 0.5, 0.75, 1 and 1.25 litre |
| Relative density | 70 %, 80 % |
| Initial water content | 0 %, 5 % , 10 % |
| Rate of water flow | 5, 7, 10 and 13 ml/sec |
| Materials | Local sandy soil , subbase type(D) |

## 4.5 Particle Image Velocimetry (PIV)

Image correlation is used to evaluate the ground displacement resulted from each drainage cycle. Therefore, digital single lens reflex cameras (DSLR) were set out at a distance of 1.5 m from the main soil chamber. Setting the camera in close vicinity to the target leading to perspective distortion in the images (Thielicke, 2014). Therefore, a maximum possible distance of 1.5 m was selected. Nikon D7200 DSLR cameras were used in the present study, this camera has 23.6 x 15.6 mm, complementary metal oxide semiconductor (CMOS) sensors and an image resolution of 6000 x 4000 pixels was chosen. To avoid relative movement between the lens and the target which can occur in automatic mode due to autofocusing, the camera and lens were operated in manual mode. To avoid the reflection of nearby objects on glass walls of the apparatus, which can disturb the images and hampers the correlation process, black cover were used behind the camera. The acquired images were processed using PIVlab (Thielicke and Stamhuis, 2014), which is a graphical user interface (GUI) tool in MATLAB (The Mathworks Inc., 2014). The program requires at least two consecutive images in JPEG format for the correlation process to be done. Ground settlement for each drainage cycle of the test near the pipe defect as well as near the surface of the model ground was obtained and assessed. For each cycle, the first image was captured before water infiltration into the model ground and the second image was captured after completing the drainage process. PIVlab permits the user to obtain the mean vertical velocity of a specific part of the image. By utilizing this tool, the settlement of the 50mm X 50mm areas above the leakage was computed and evaluated for different depths.

# Chapter Five

## Results And Discussion

## 5.1 Introduction

This chapter presents analysis and discussion of the data, which were obtained from the experimental work. Experiments are conducted to investigate the mechanism of soil erosion induced by defective sewer pipes, the effects of the potential influencing parameters were analyzed and assessed. Also, Particle Image Velocimetry (PIV) was utilized to explore the soil erosion process by using image visual analysis. Based on the dimensional analysis, a simple statistical model was established for estimation of eroded sandy soil through a defect on a sewer pipe.

## 5.2 Exfiltration/infiltration cycle number

The process of water exfiltration and soil drnaige through sewer pipe defect is called cycle (C). Throught the experimental work observation, each cycle process can be divided into four stages. Stage (1), is before the water inflow into the model. Stage (2), represents the end of water inflow. Stage (3), represents the end of water stabilisation (2 minutes after 2nd step). Stage (4) is the end of the drainage (the end of the water exfiltration/infiltration cycle). In Stages 2 and 3, the soil becomes saturated and the capillary force between soil particles start to disappear, this process produces potential weakened zones in the model ground. Thereafter, in Stage (4), water starts to flow in the direction of the leakage as the drainage plug is unlocked. Therefore, soil particles that are located close to the leakage are most likely to be washed out first, this was very clear from the very early cycles. After the completion of the water drainage process, capillary force between soil particles starts to build up again and this is because of the departure of water. The process of cavity formation usually occurs during the third cycle where the effective stress between soil particles in the weak zones is close to zero. Typical cavity often is fan shaped, arching on the top, and slope on both sides, Fig (5-1).

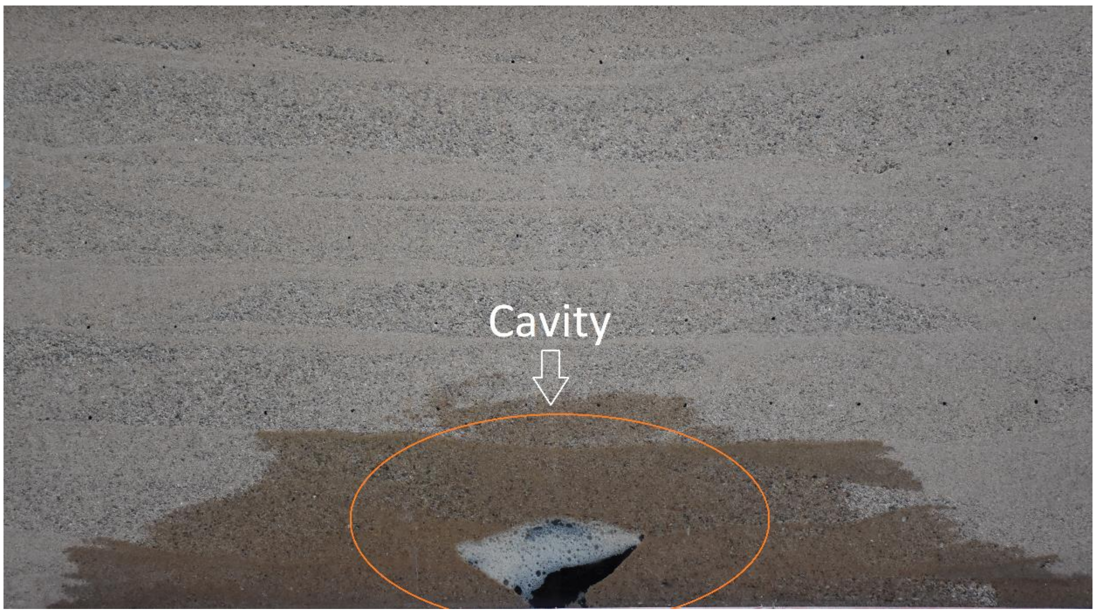


Figure 5-1 Picture of a cavity form

Similar shape of the cavity was recognized by Sato and Kuwano (2010). They explored the erosion process by conducting laboratory model tests. Size of the cavity increases with the increasing number of cycles. It was observed that for the size of the cavity to be increased. It is necessary for the water table to ascend above the cavity to moisturize the soil at the cavity ceiling. Soil erosion happens during water inflow and drainage cycles before and after cavity formation, and even if the cavity did not expand the fine soil still erode with water. Fig (5-2) shows soil erosion through the cycles.

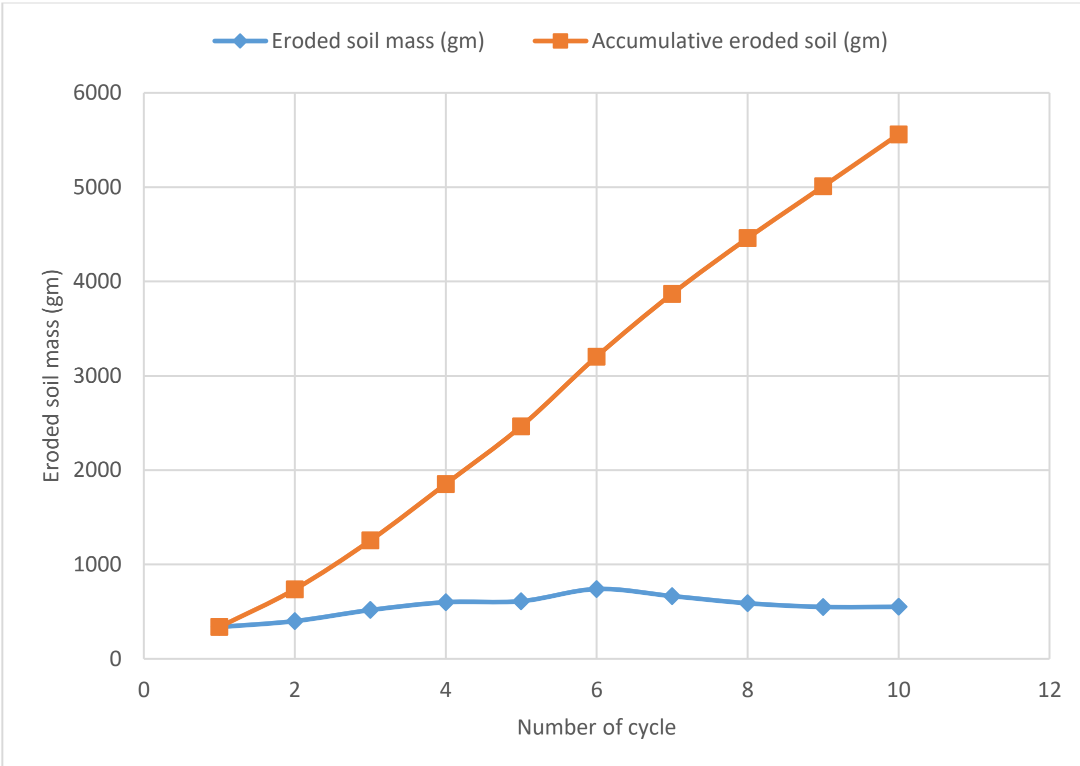


Figure 5-2 Soil erosion through cycles

## 5.3 Inflow water volume

five different volumes of inflow water were used 0.25, 0.5, 0.75, 1 and 1.25 litre, each volume supplied into the soil chamber through the leakage for 10 cycles. The soil is compacted to 80% of relative density. The test running was done for each volume separately. Weight of soil loss for each volume is plotted against cycles in Fig. (5-3) and the accumulated weight of soil loss is plotted against cycles Fig. (5-4).

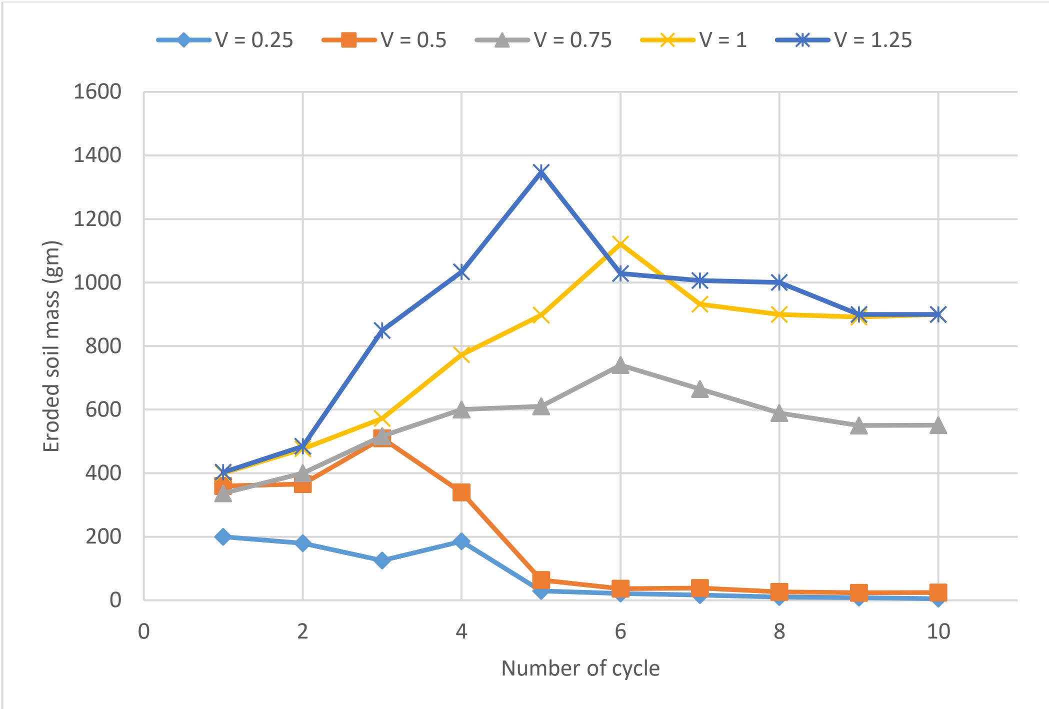


Figure 5-3 Eroded soil mass against cycle number for different volumes of water inflow

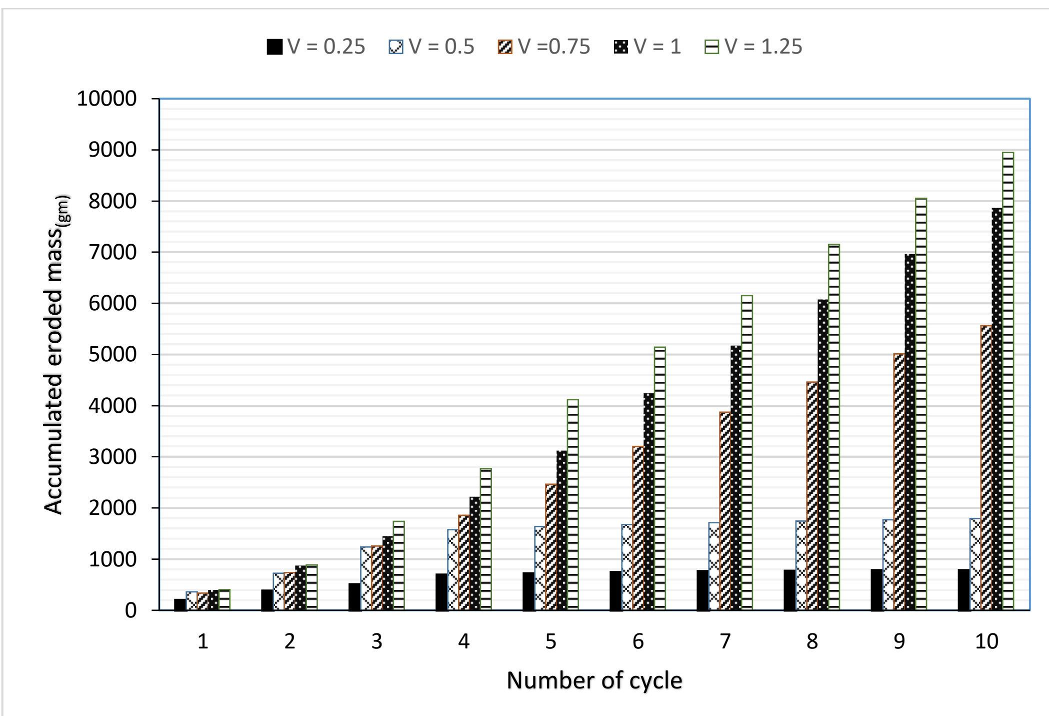


Figure 5-4 The accumulative soil mass against cycle number for different volumes of water inflow

It is clear that larger volume of water led to larger amounts of soil loss. Larger volumes of water reachs more areas in the soil than smaller volumes and carry more soil particles into drainage through the leakage.

It was observed that the larger volumes had a contineuos erosion process during the cycles of the test. The erosion was contineuos when the volume of water 0.75 litre or more. While the rate of erosion became very low after cycle (4-5) in 0.25 and 0.5 litre as shown in Fig. (5-4), the reason of that is small volumes of water had an impact on a limited area of the model ground, and also, the erosion was decreased after a number of cycles (4-5 cycles) due to depletion of disturbed soil particles . The difference in the amount of soil loss between larger volumes and smaller volumes were expanding to large differences in the late cycles, due to continued erosion process of the larger water volumes, which remain continuous until the failure of the model ground.

Height of water level in the experimental soils was observed for each inflow water volume and the relation between the volume of water and the height of water level (Hw) is plotted in Fig (5-5).

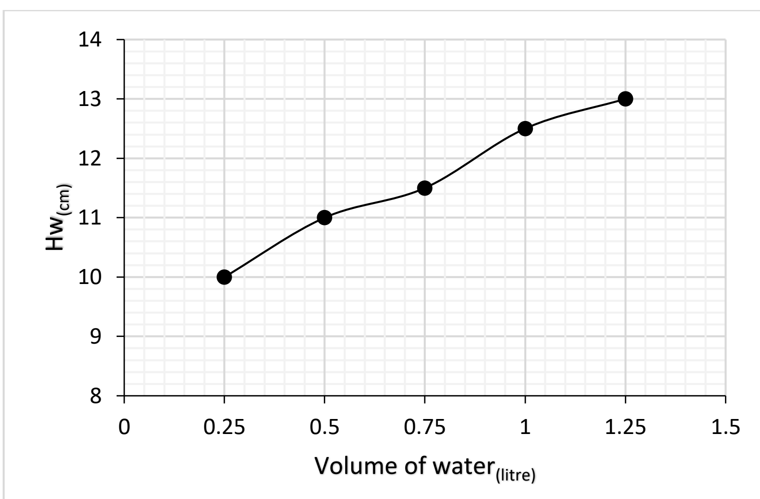


Figure 5-5 The relation between the inflow water valume and the water level in soil

Figure (5-5) demonstrates that for this particular soil (Hw) increases with increasing volume of water (V). Fig (5-6) shows the effect of ratio between height of water level and soil particle size in terms of dimensionless parameter ($Hw/D_{70}$) on the total eroded soil at cycle 10, where: $D_{70}$ is the experimental soil particles size distribution property.

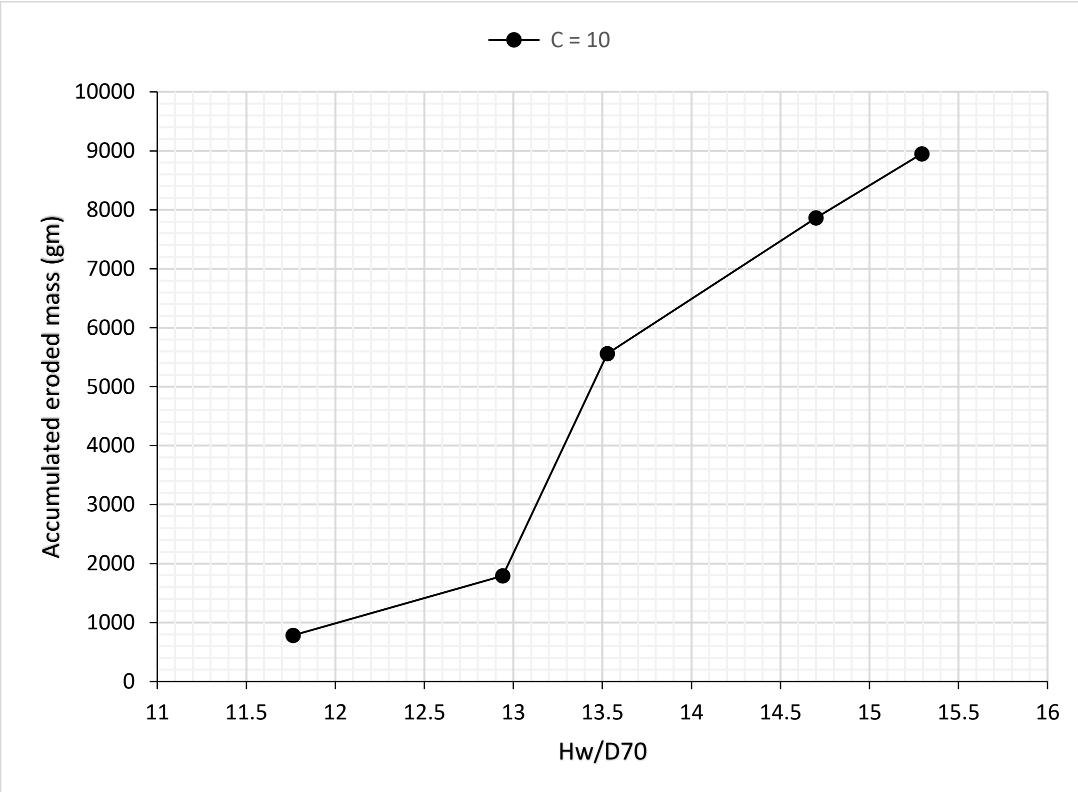


Figure 5-6 Effect Of Water Level On Soil Erosion

It can be observed in Fig.(5-7) that the increasing in the water height of the soil means more water spread, and thus more increase in the amount of soil affected by it. Therefore, more soil particles will be released and transported with water during the drainage process into sewer pipe through the leakage. Moreover, the increasing in the height of the water level in the soil causes an increase in pressure on the leakage opening which leads to push more soil into the sewer pipe.

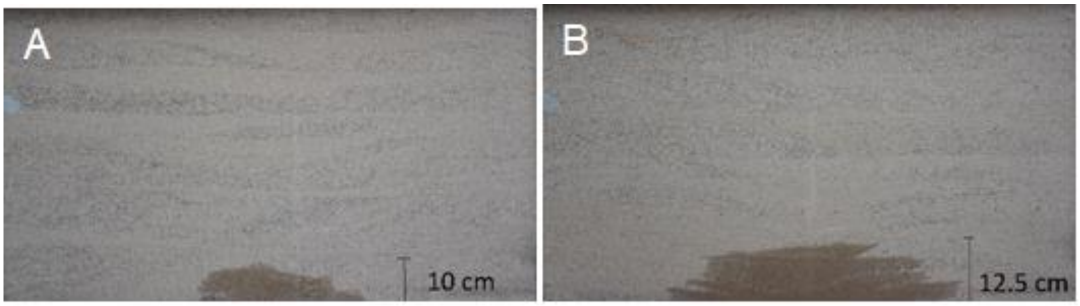


Figure 5-7 The height of water level when: A) v = 0.25 and B) v = 1 litre

In general, the result demonstrates that the total amount of eroded soil mass ( measured after model ground failure) increased by 40% for each 10% increment in the height of water (Hw) .

Cavity formation process is observed and it appears to be effected by the volume of inflow water. Cavities were expanding faster during the test cycles when the model ground is supplied with large volumes (0.75, 1 and 1.25 litre), Fig. (5-8).

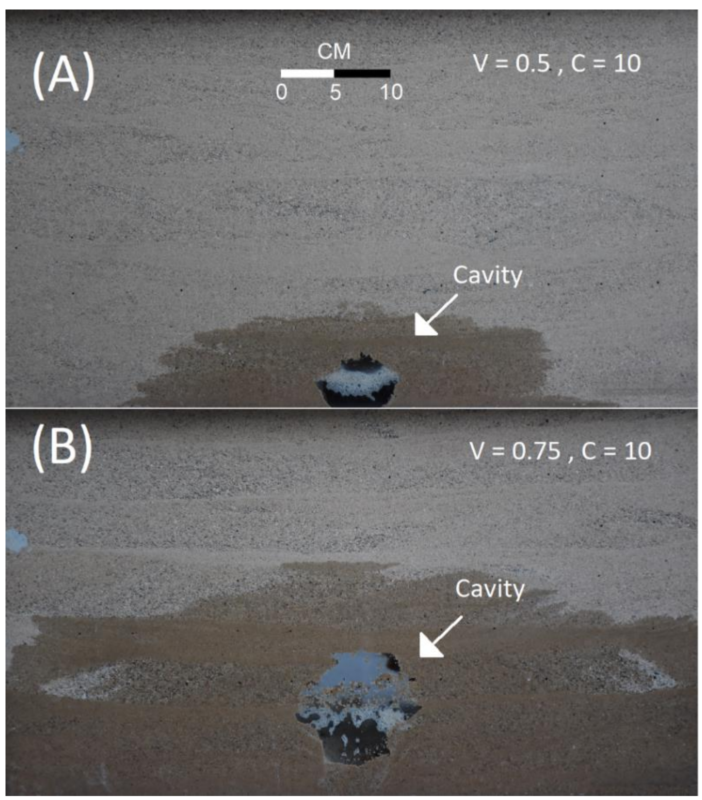


Figure 5-8 The effect of water inflow volume on the cavity formation

## 5.4 leakage width

Soil erosion through a defect on the pipe is related to the particle size and opening size. Therefore, the leakage width is controlled to study soil particle behavior. Five sizes of leakage width were used: 3,4,5,6 and 7mm. For each leakage width, the run was done with inflow water volume of 0.75 liter and the soil was in dry condition with 80% of relative density.

Fig. (5-9) shows the accumulative eroded soil mass against number of cycle for each leakage width. It is clear from the results that leakage size has crucial effect on the amount of eroded soil, where the amount of collected soil increases with the increasing of the leakage width. There is a huge difference in the amount of total eroded soil mass between the different leakage sizes, where: : 7mm of leakage width has 14.5 times, 6mm has 13.4, 5mm has 13 and 4mm has 6.4 times the amount of eroded soil mass compared to the amount of eroded soil mass collected through the leakage width of 3mm.

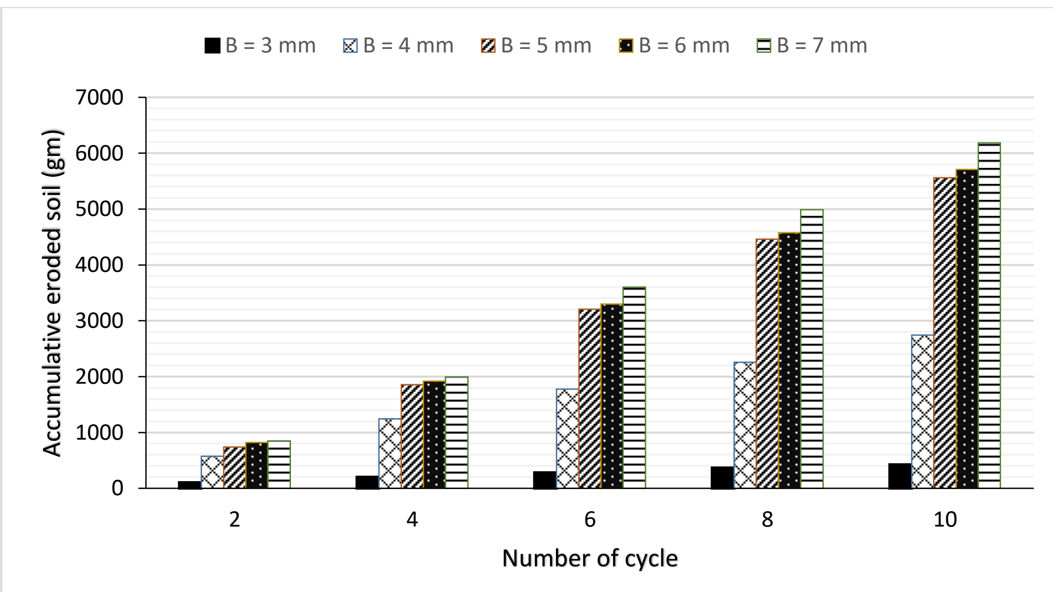


Figure 5-9 The effect of leak width on the total eroded soil during test cycles

To realize the relation between the amount of eroded soil and soil particle size, $D_{70}$ was used to refer for soil particle size in the present study, where: $D_{70}$ is the sieve size through which 70% of the weight of soil sample passes. By realizing the results, the relationship between the total eroded soil mass and the ratio of $D_{70}$ to the leakage width is drawn in Fig. (5-10) . It was found that the amount of collected eroded soil increased when the ratio of $D_{70}$/B decreased. In general, through the experiments, when the ratio of $D_{70}$/B is less than 0.17, the eroded soil enters the eroded soil collection unit through the leakage easily and continuously.

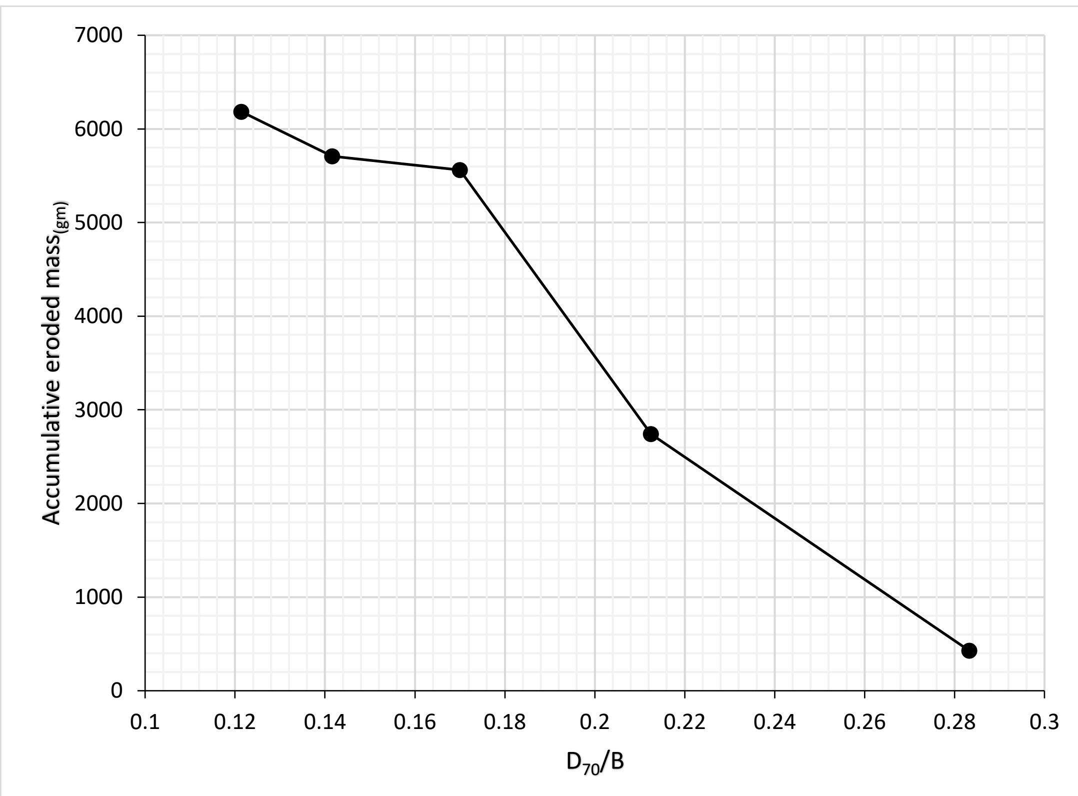


Figure 5-10 The effect of the ratio (D70/B) on total amount of eroded soil at the end of 10 cycles

In order to identify the soil particle sizes that are more likely to be eroded by water supply/drainage cycle. Eroded soil through different leakage sizes were collected with each cycle then it were sieved separately. Sieve analysis for eroded sandy soil shows that soil particle sizes of less than 0.42mm is more prone to erosion, while larger sizes were more resistant where the greater the leakage width, the greater the proportion of soil with a size greater than 0.42mm, but its percentage was always less than the original soil. Furthermore, the early cycles has larger percentage ratio of fine sizes than late cycle for all leakage widths.

## 5.4 Initial water content

The accumulated weight of soil loss in three different water content conditions: dry, 5% and 10% in local sandy soil with 80% of relative density is plotted against cycles in Fig (5-11).

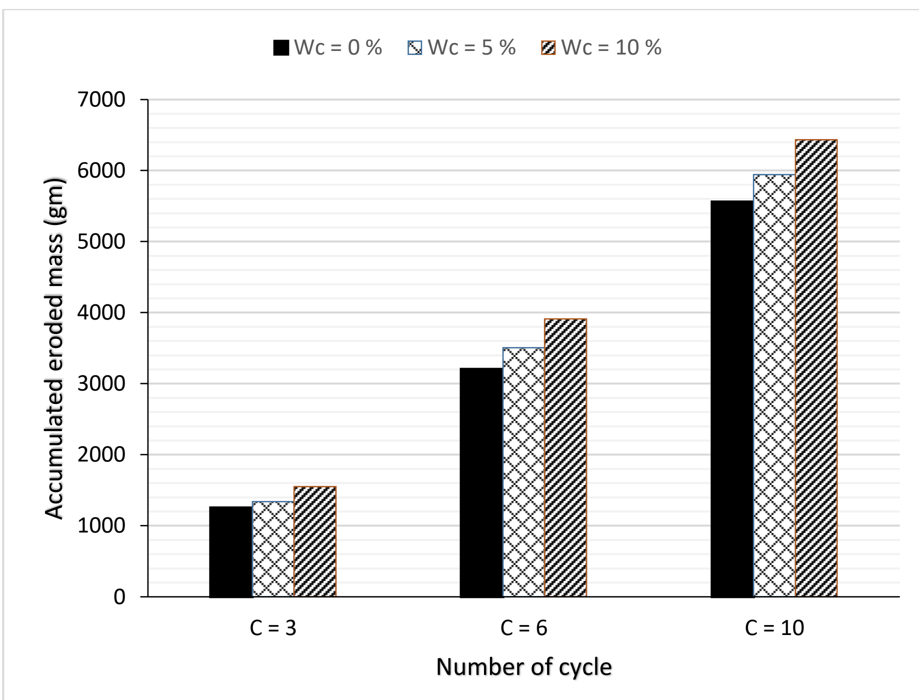


Figure 5-11 The effect of water content on soil erosion, B=5mm

The results show that the soil with higher intial water content has higher amount of soil loss. Soil with 5% of initial water content has 7% more amount of eroded soil mass, while soil with 10% of initial water content has 16% more amount of eroded soil mass. Also, it can be found that weak area of soil formed around the cavity in the soil with higher initial water content Fig. (5-12).

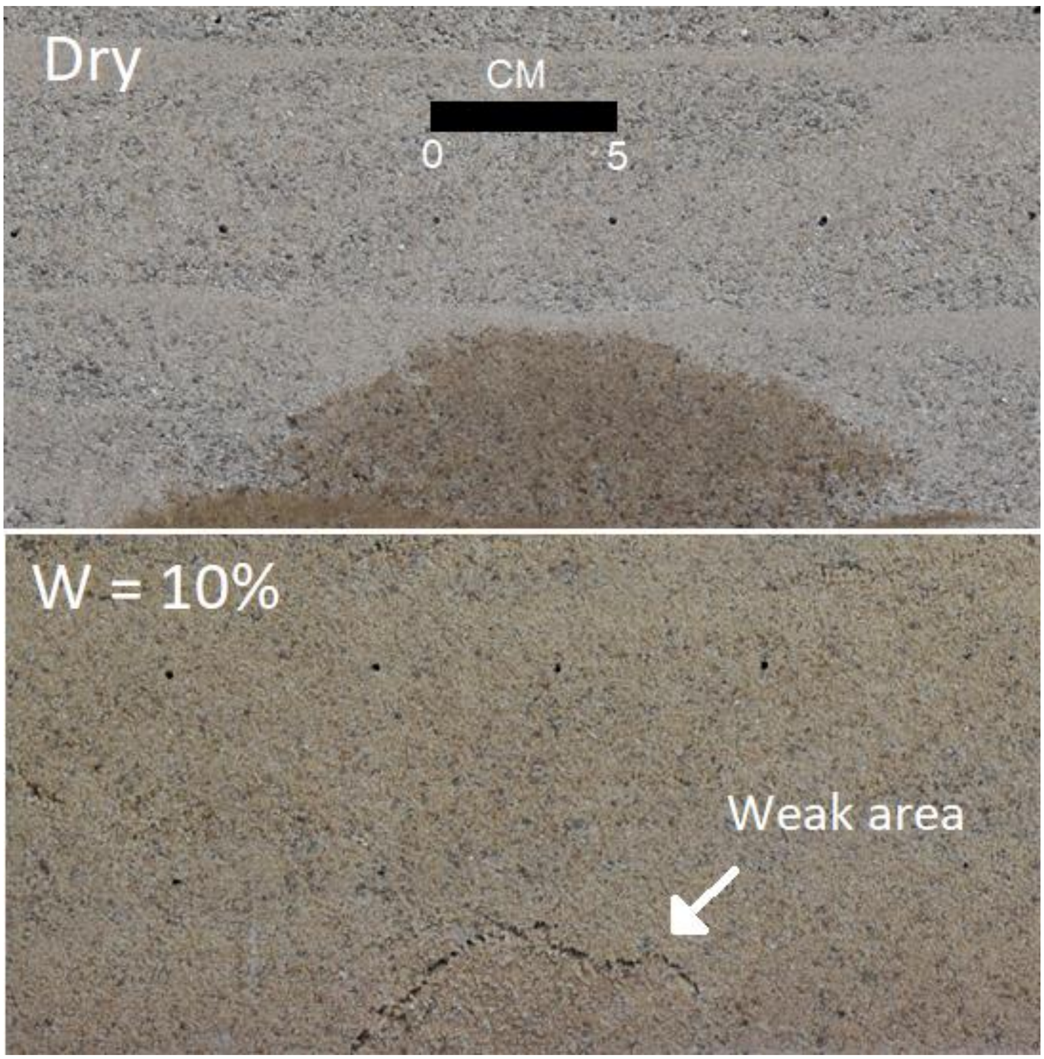


Figure 5-12 Picture shows weak area around the cavity in soil with 10% water content

These results can be attributed to that when the soil becomes saturated, the capillary force between soil particles will be lost, and this action creates potential weak areas in the soil model and increases the amount of eroded soil particles.

## 5.5 Relative density

To test the effect of relative density on soil erosion process. Two different amounts of relative densities were used 70% and 80% with 0.75 litre, water inflow volume and 5mm leakage width. Fig. (5-13) shows the results of eroded soil against cycle number, while Fig. (5-14) shows the accumulative eroded soil against cycles.

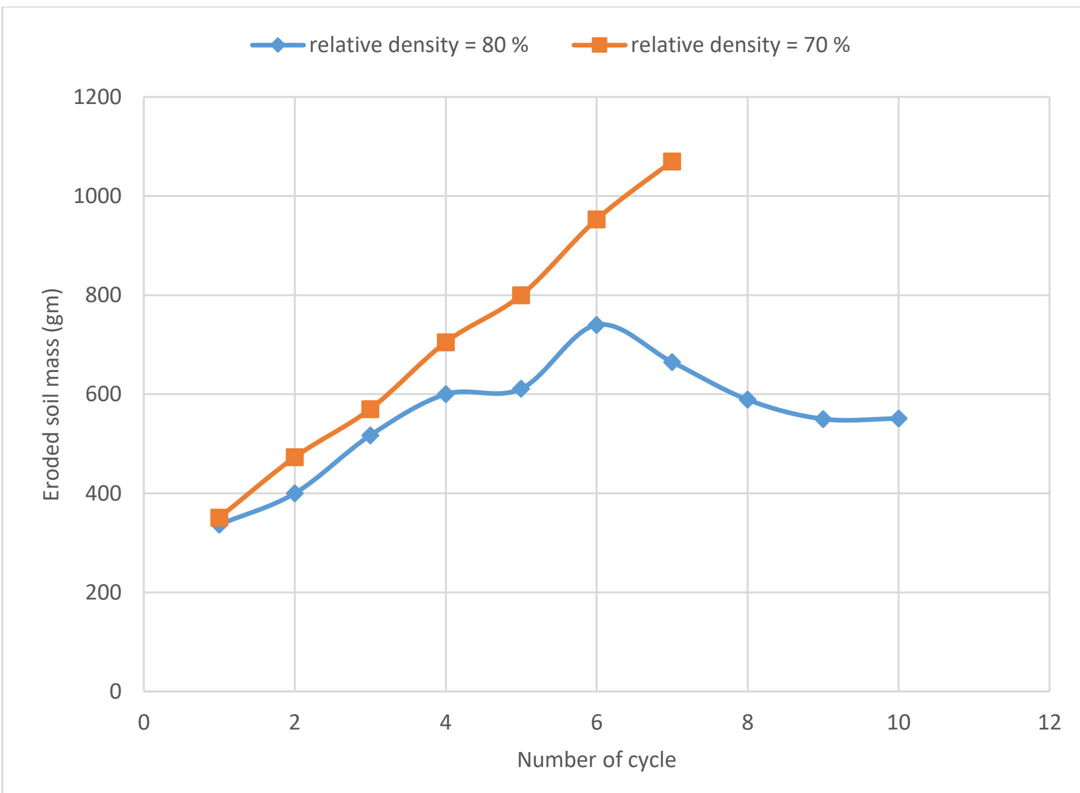


Figure 5-13 The effect of relative density on soil erosion duting test cycles

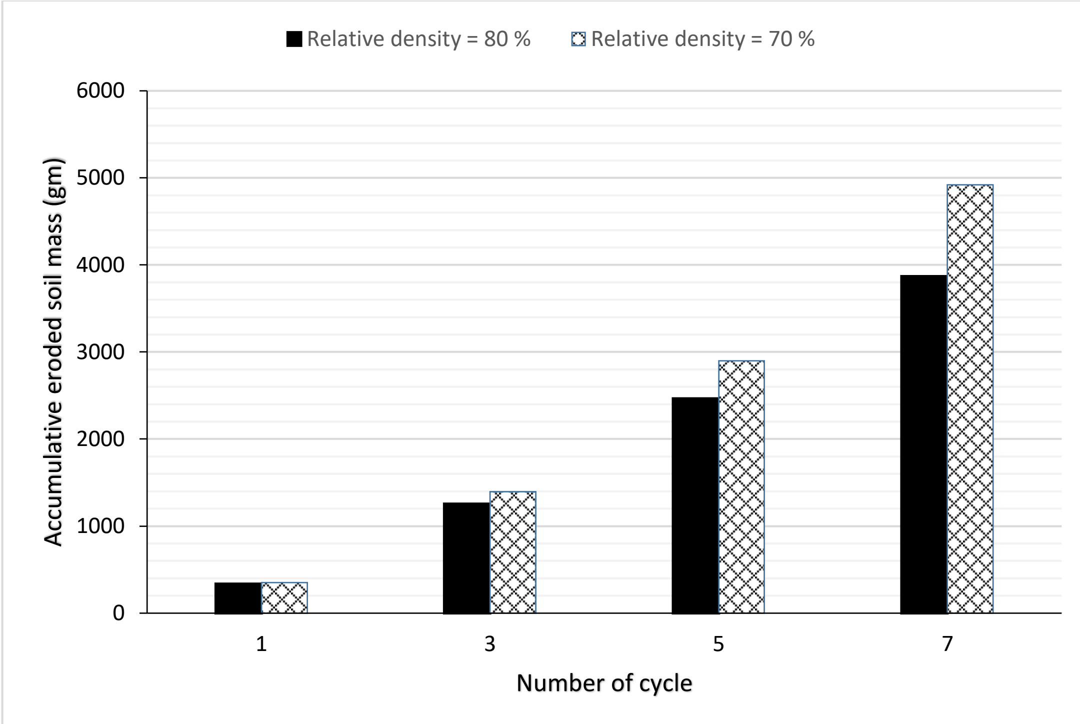


Figure 5-14 The accumulative eroded soil mass for soil with different relative densities

The resuls show that the amount of collected eroded soil is decreasing with the increasing value of relative density. In the case of 70% of relative density the collected eroded soil was 27% greater than the case in which the soil was 80% of the relative density. For the soil with 70% relative density the rate of soil loss increased continuously and the soil collapsed after cycle seven, while the soil with 80% relative density collapsed in the twelfth cycle. The movement of vertical soil layers was significant in the soil of lower density and this will be explained in the next topic (PIV lab).

The increasing in the amount of eroded soil in a low-relative density soils can be attributed to the change in the soil's hydraulic properties, allowing water to move and spread more easily, as well as to the change in soil characteristics. in a low-relative density soils, soil particles are less cohesive and more likely to escape their locations under the effect of cyclic water flow.

## 5.6 PIV lab

Tracking of soil particle movement related to each test cycle was achievable utilizing PIV analysis. Velocity profile before and after cavity formation is presented in Fig. (5-15).

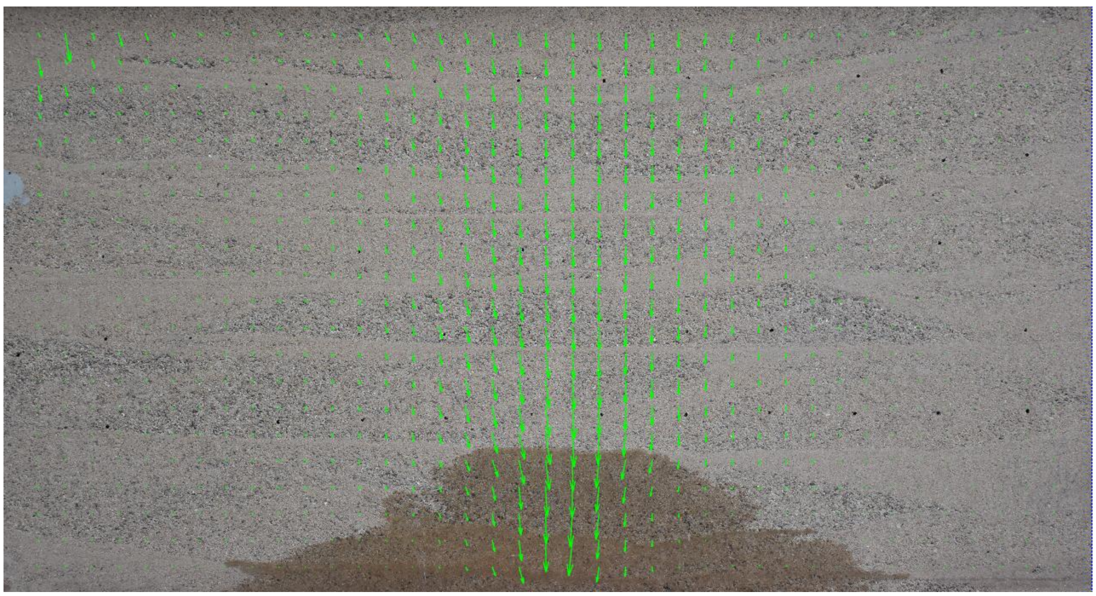

Figure 5-15 Velocity profile of soil particles by using PIV

Saturated area close to the water inlet could not be analysed, because of the existence of high amount of water, which causes image distortion. As a result, soil displacement in that spot is not accurately measurable by using PIV analysis. Downward arrows refer to the soil particles moving downward from the original position. PIV analysis allows the determination of soil particles movement path and the region that influenced by extensive deflection.

### 5.6.1 Evaluation of vertical deformation

Using PIV lab, horizontal and vertical components of the velocity for cycle was found. This method creates a high vector resolution (vectors per unit area) within the image. The displacement distribution in whole model space is plotted in Fig. (5-15), based on the mean area velocities calculated above mentioned. The mean aera velocities hisogram for the model ground is shown in Fig. (5-16).

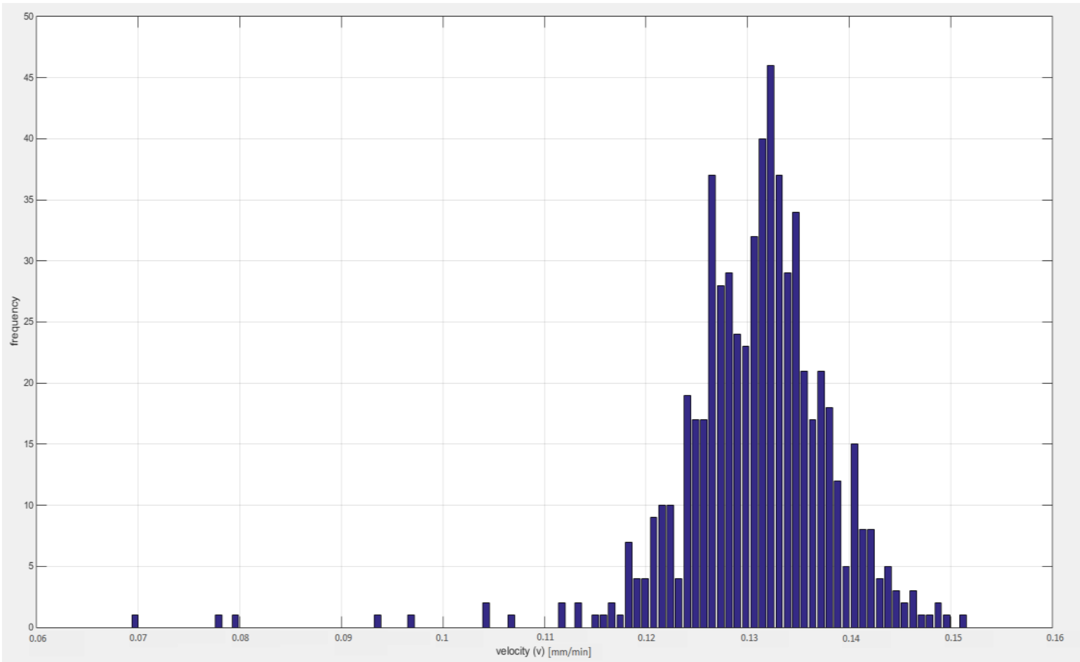


Figure 5-16 Mean area vilocities given by PIV lab

Inspection of Fig. (5-15) reveals that the settlement of soil layers was concentrated in the central region, which was located over the pipe defect. Similar trends was noticed in all the experimental tests in different conditions.

To simplify the interpretation of the deformation profile in model space, the area mean velocity of a 50 x 50 $mm^2$ of the first layer in the model space above the pipe defect (as shown in Fig. (5-17)) was considered. Only vertical component of mean velocity vector of the 50 x 50 $mm^2$ was calculated and downward movement was considered as settlement, the results is shown in Fig. (5-18).

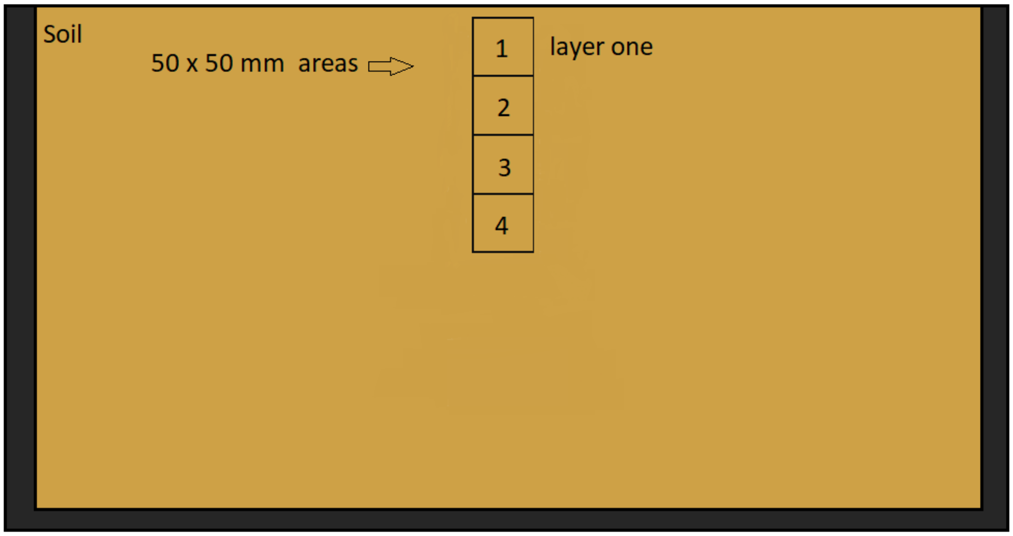


Figure 5-17 Schematic diagram shows the spaces and layers that are being monitored in the model ground

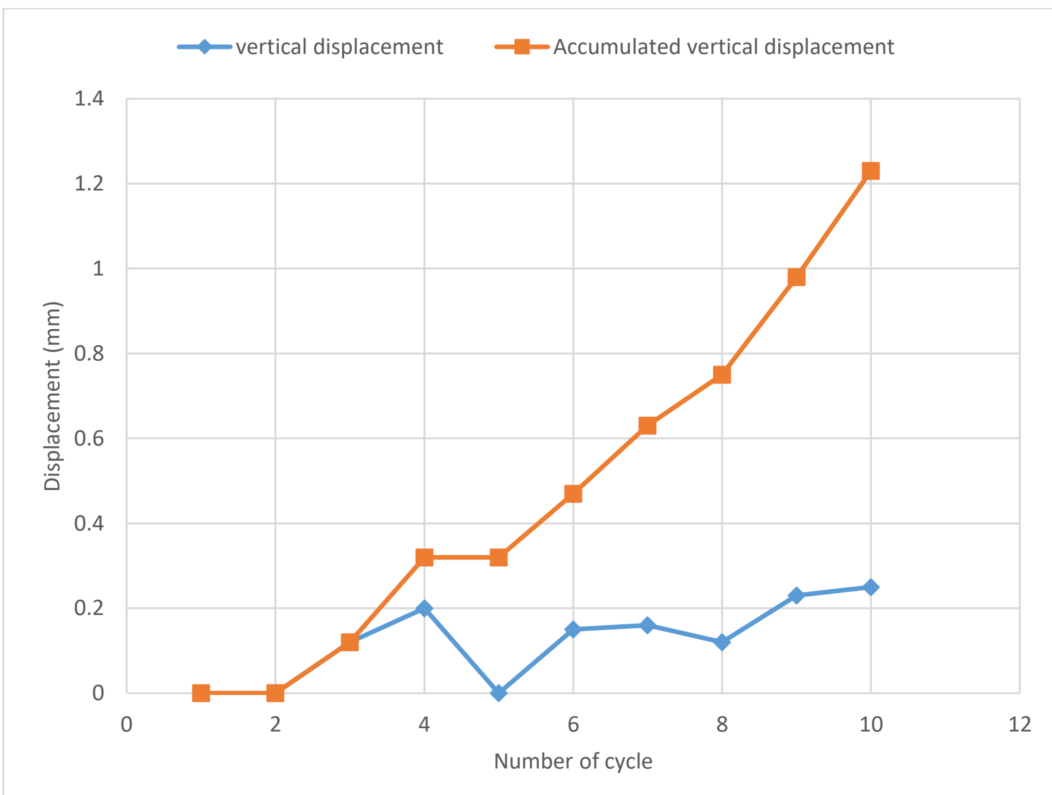


Figure 5-18 The virtical displacement of soil near the ground surface over the pipe defect during test cycles

This graph shows that the process of soil descent continued through most of cycles. Through the experiments, it was observed that the process of soil descent and cavity formation occurs during the water inflow and during drainage as well. By the examination of the results Fig. (5-18), it can be observed that the first two cycles displacements reading were zero, The displacement began to increase from the third cycle when the cavity began to form. Soil continued to descent, even after the slow expansion of the cavity, where the degree of saturation was increased in the lower layers and hence, settlement occurs throughout the layers due to the reduction of the pore water pressure which reduces the apparent cohesion of the partially saturated ground.

It was observed during the experiments that relative density had a significant effect on the amount of soil descent.

Figures (5-19) and (5-20) show that the soil of 70% of relative density has significantly larger vertical displacement than the soil with greater relative density, and for all cycles (the total settlement in the soil with 70% of relative density was 13.33 times greater than the settlement in the soil of 80% relative density). Where as shown previously, the soil of 70% relative density has more amount of eroded soil than dense soil, that means more voids were left and more movement of soil particles to generate arching holding the soil body to prevent it from collapsing over the cavity.

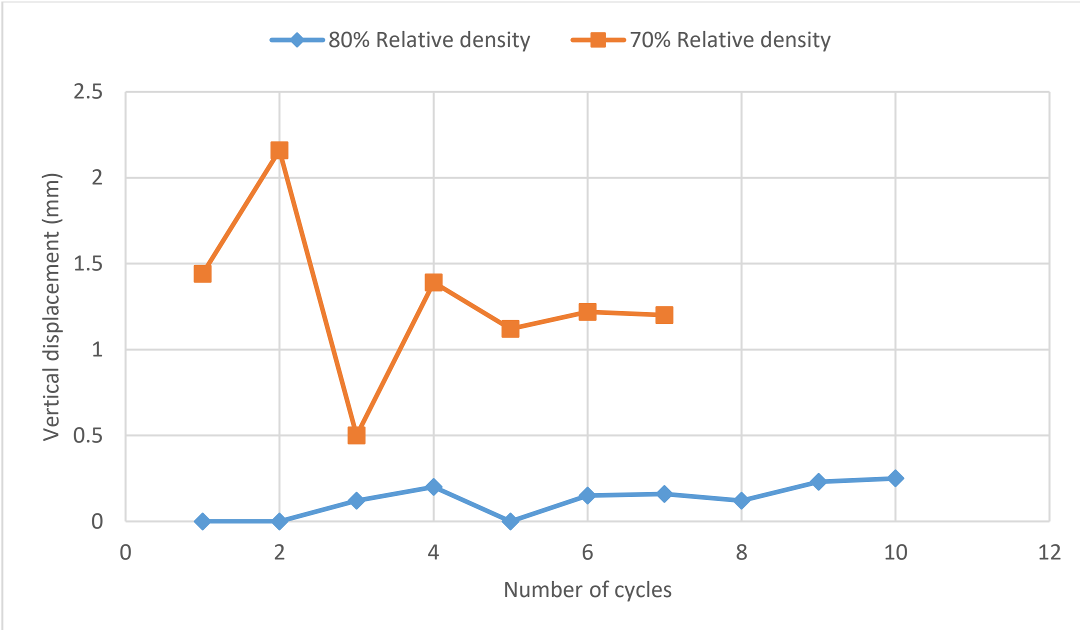


Figure 5-19 Soil vertical displacement during test cycles

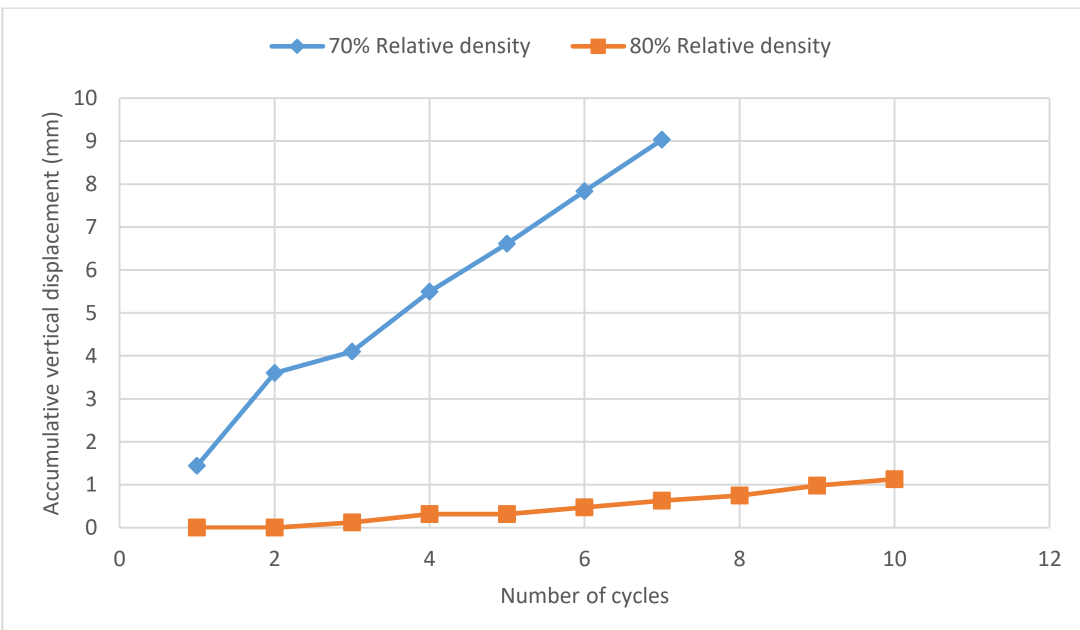


Figure 5-20 Accumulated vertical displacement during test cycles

To fully understand the deformation profile in model space and the influence of sewer depth on ground surface displacement. The difference in the deformation behaviour close to the cavity and close to the ground surface were considered. The vertical displacement was monitored for four different depths (as presented in Fig. (5-17)). Individual and cumulative displacements over the pipe defect at the 1st , 2nd , 3rd and 4th layers for all test cycles are plotted in Figures (5-21) and (5-22).

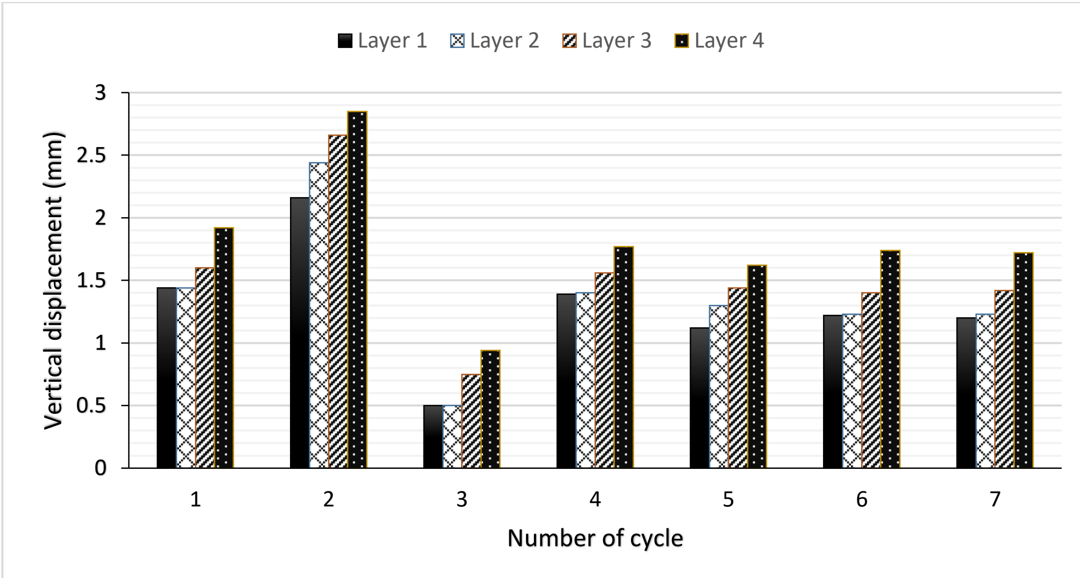


Figure 5-21 Vertical displacement of soil layers during test cycles (Relative Density = 70%)

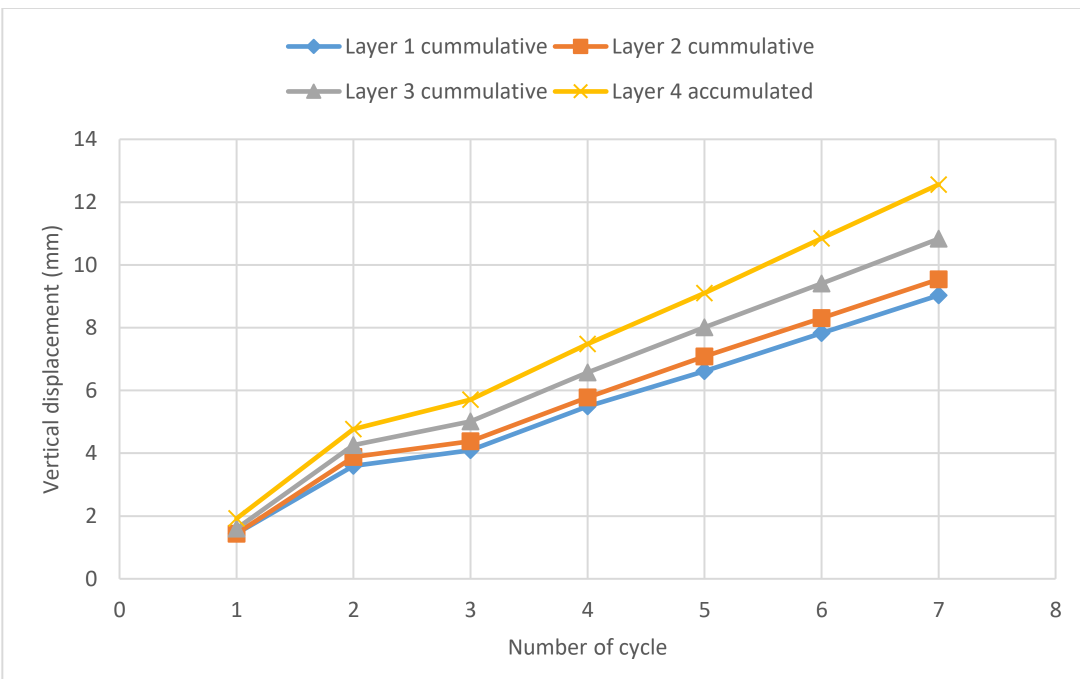


Figure 5-22 Accumulated vertical displacement of soil layers during test cycles (Relative Density = 70%)

The results show that the higher the layer depth, or the closer the layer is to the cavity, the greater the displacements. Thus, the higher the depth of the soil above the sewer pipe , the lower the apparent settlement on the surface.

## 5.7 Comparison of subbase and local sandy soil

Subbase type (D) is used as a sewer pipe embedment material according to the iraqi specification. Thus a comparison between its performance and its susceptibility to the erosion, and the performance of the local sandy soil is necessary. Subbase type (D) is used in the same way with different leakage sizes and water inflow volumes.

Fig. (5-23) shows the effect of leakage width on the amount of total eroded mass.

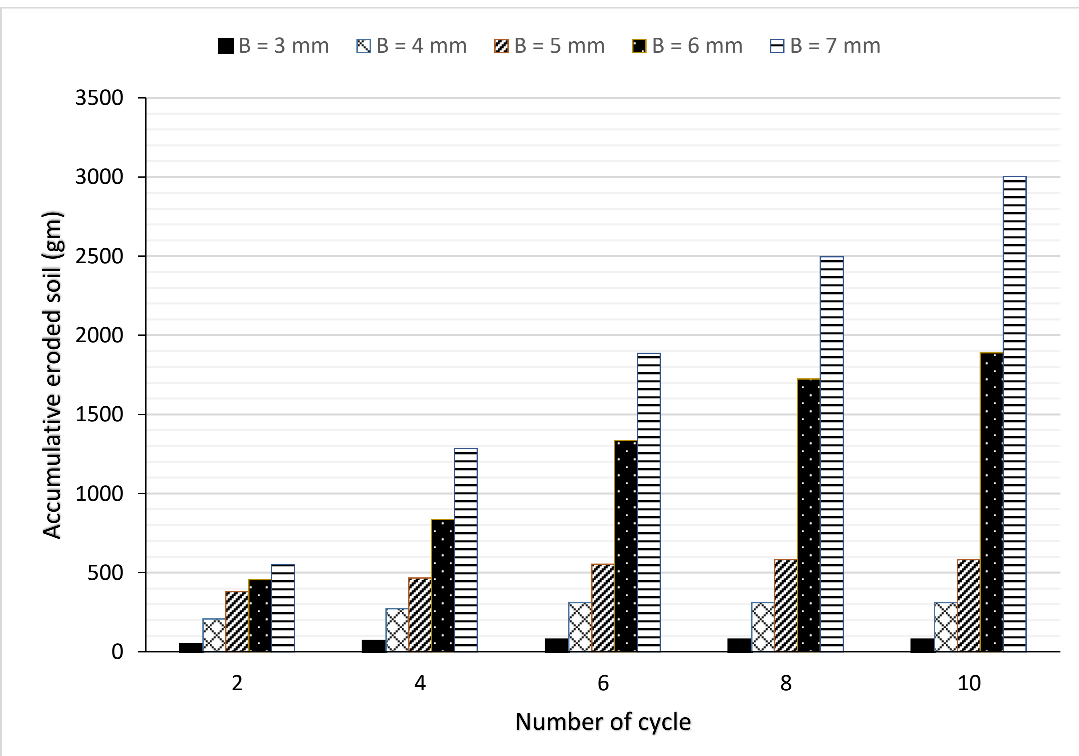


Figure 5-23 The effect of leak width on amount of eroded soil ,(Subbase)

Fig. (5-24) shows the relation between the ratio of leakage size to the particle size with the total eroded mass.

The results show similar behavior, as the amount of soil increases with the increasing of the leakage width, and the amount of eroded soil increases with the decrease of the ratio of ($D_{70}$/B).

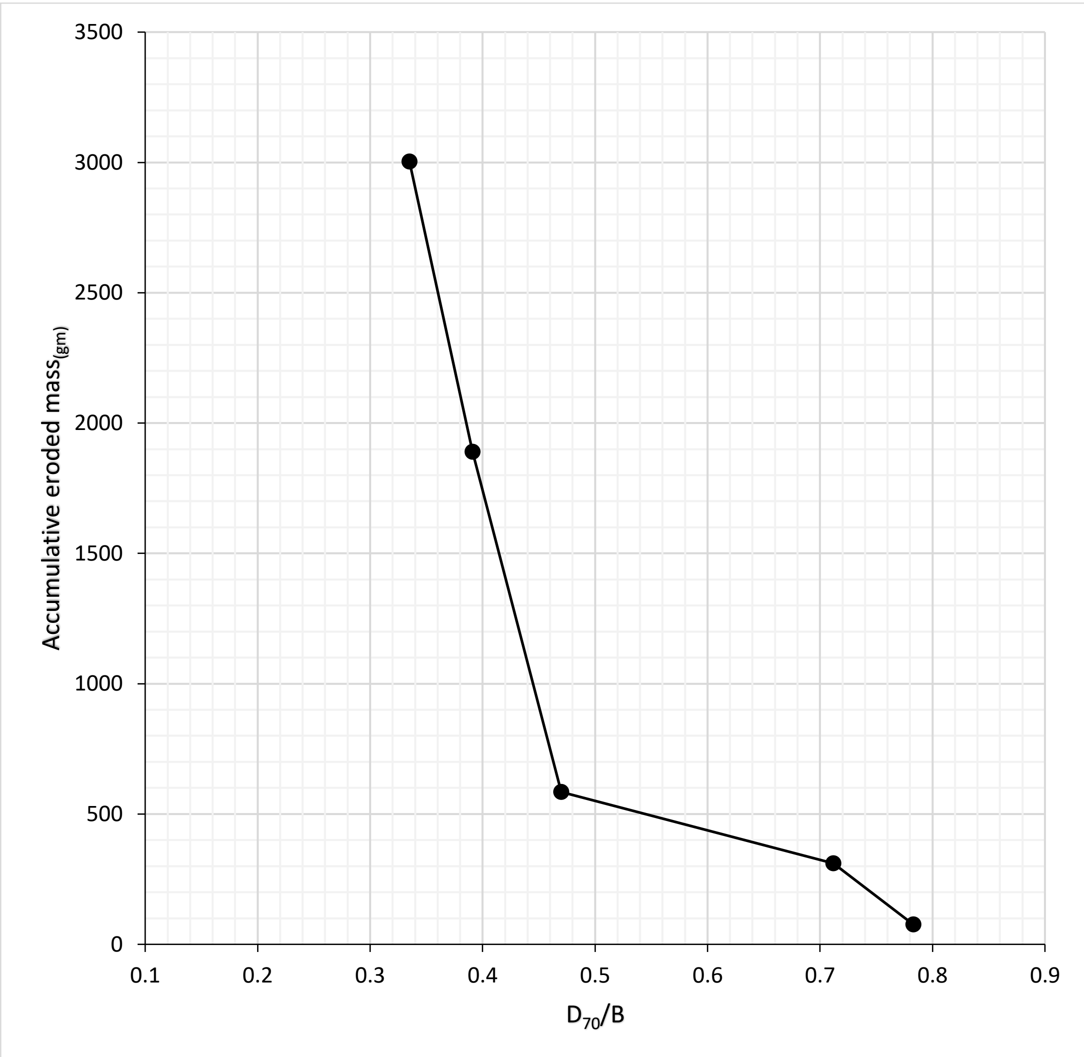


Figure 5-24 The relation between (D70/B) and total eroded soil

Fig. (5-25) shows the comparison of the total eroded soil mass at end of the 10 cycles in both subbase and sandy soil. It is clear that sandy soil eroded in larger quantities through all leakage sizes. Where the ratio between the total eroded subbase mass and the total eroded sandy soil mass ($\frac{E_{subbase}}{E_S}$) is shown in Table (5-1).

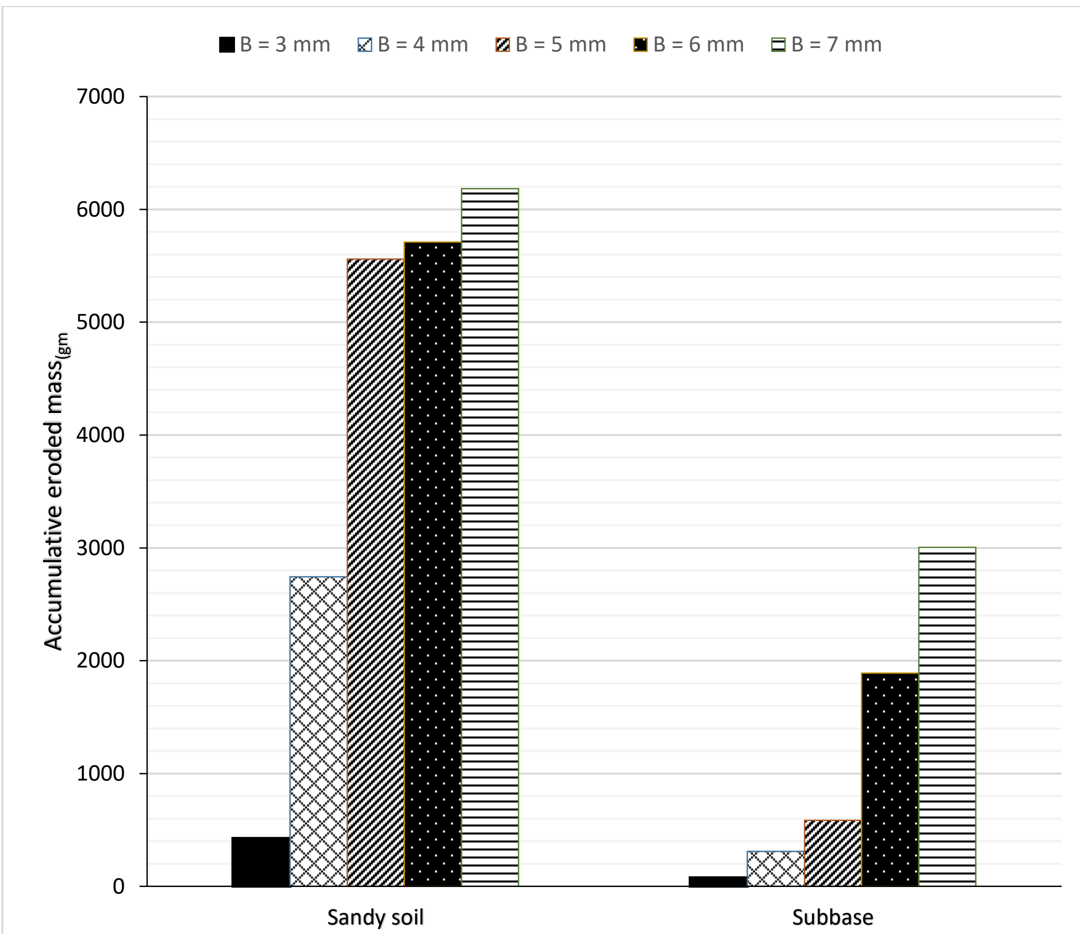


Figure 5-25 The total eroded soil at the end of 10 cycle through each leak size

Table 5-1 The ratio between the total eroded subbase mass and the total eroded sandy soil mass

| Leak width $_{mm}$ | $\frac{E_{subbase}}{E_s}$ % | $\frac{D_{70(subbase)}}{\text{Leak width}_{mm}}$ | $\frac{D_{70(sandy\ soil)}}{\text{Leak width}_{mm}}$ |
|---|---|---|---|
| 3 | 17.7 | 0.78 | 0.28 |
| 4 | 11.3 | 0.58 | 0.21 |
| 5 | 10.5 | 0.47 | 0.17 |
| 6 | 33.1 | 0.39 | 0.14 |
| 7 | 48.5 | 0.33 | 0.12 |

The results indicate that the amount of total eroded soil increases significantly when the ratio of ($D_{70}$/B) become close to the value of 0.17, like previously concluded in the sandy soil tests. It is important to point out that during the experiments, the erosion of the subbase stopped when using a 3 mm and 4 mm leakage width after about (5-6) cycles due to the closure of the leakage. The reason of why subbase is more resistant to erosion than the local sandy soil through the same leakage sizes is the larger size of subbase granules ($D_{70(subbase)}$ = 2.35mm, $D_{70(sandy\ soil)}$ = 0.85mm ) and the higher amount of clay content that led to the closure of the small leak sizes during the test.

Fig (5-26) shows the effect of volume of water inflow on the amount of eroded soil. From the results of the experimental works, it can be seen that the subbase has more resistance to water diffusion than local sandy soil, Which it was limited in less area. Sometimes water was trying to climb up between the soil and the glass wall , due to the lack of subbase permeability. In addition to the large size of subbase granules ($D_{70(subbase)}$ =2.35mm, $D_{70(sandy\ soil)}$ =0.85mm ), the amount of eroded soil was less than in the sandy soil, where the subbase was less affected by the change in the volume of water inflow. After comparing the effect on both of subbase and local soil by changing the volume of water inflow between the largest volume and the lowest volume causing continuous erosion. Results showed that in case of sandy soil, the percentage of increase in the eroded soil mass was 60%, while in the subbase was 41%, this makes subbase more resistant to the change of water inflow volume by 19%.

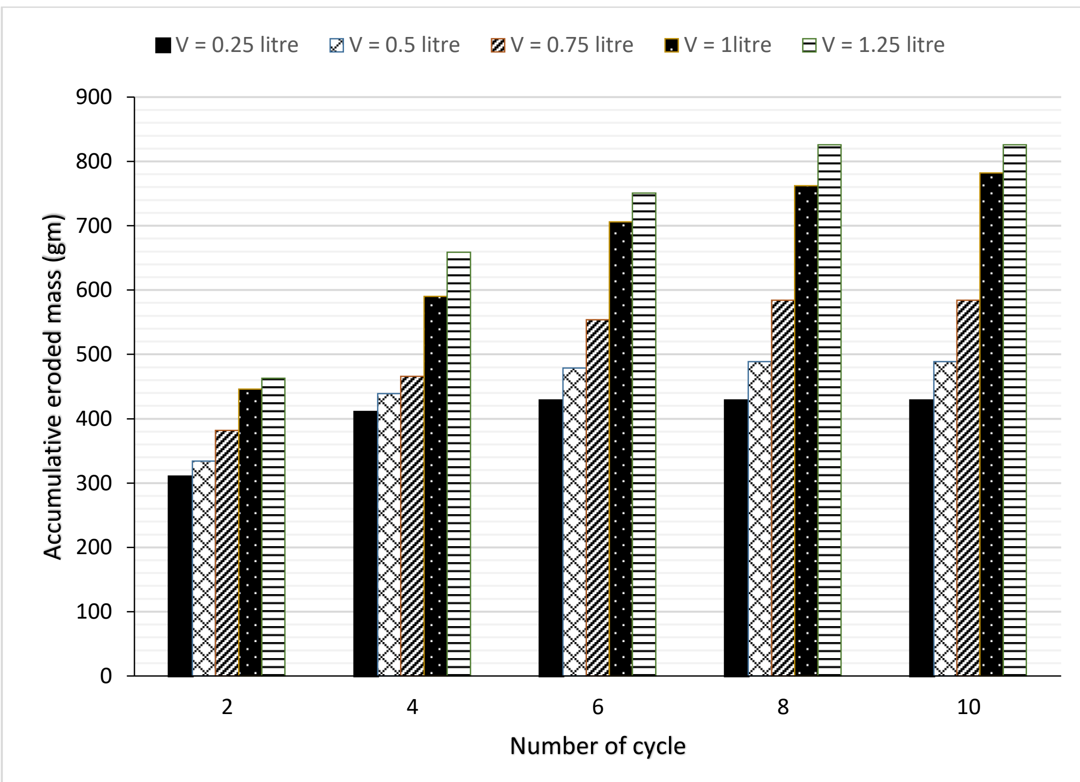


Figure 5-26 The effect of water inflow volume on the amount of eroded soil, (subbase)

In general, the experimental tests showed that the sandy soil was significantly more susceptible to erosion than subbase; The sieve analysis for the eroded subase through different leakage sizes showed that soil particle sizes of less than 0.3mm were more prone to erosion while larger sizes were more resistant.

## 5.8 Dimensional analysis results and Prediction Model

Experimental tests performed on local soil using varying matrix of influencing factors as shown in Table (5-2), and the dry eroded soil mass was measured for each cycle. The collected results is 256 dataset of cycles, divided randomly into 189 cycle to generate the model and the other 67 dataset was used to validate the model (Appendix-B). Since the dependent variable is the total (accumulated) eroded soil mass, then the other dimensionless groups was multiplied by the number of cycle (C) to show their effect in the cyclic flow. The data was analyzed using SPSS and correlated using Pearson correlation. The results show that the leakage width has the largest impact on the rate of erosion.

Table 5-2 Experimental tests matrix

| B(mm) | Hw(mm) | W(%) | **Q**ml/sec | C |
|---|---|---|---|---|
| 3 | 11.5 | 0 | 10 | 1 … 10 cycle for each Hw value |
| | 12.5 | | | |
| | 13 | | | |
| | 11.5 | 10 | | |
| | 12.5 | | | |
| | 13 | | | |
| 4 | 11.5 | 0 | | |
| | 12.5 | | | |
| | 13 | | | |
| 5 | 11.5 | 0 | | |
| | 11.5 | | 13 | |
| | 11.5 | | 7 | |
| | 11.5 | | 5 | |
| | 12.5 | | 10 | |
| | 13 | | | |
| | 11.5 | 5 | | |
| | 12.5 | | | |
| | 13 | | | |
| | 11.5 | 10 | | |
| | 12.5 | | | |
| | 13 | | | |
| 6 | 11.5 | 0 | | |
| | 12.5 | | | |
| | 13 | | | |
| 7 | 11.5 | 0 | | |
| | 12.5 | | | |
| | 13 | | | |
| | 11.5 | 10 | | |
| | 12.5 | | | |
| | 13 | | | |

Fig. (5-27) shows the strong positive relationship between the ratio of leakage width to soil particle size (B/$D_{70}$), and the rate of erosion (Es/ ρ $D_{70}^3$). The correlation value is 0.87. The erosion rate increases with increasing of the ratio of (B/$D_{70}$), where larger leak width means larger amounts of soil that can be carried by the water into the sewer pipe, while the converse is true for the soil particle size.

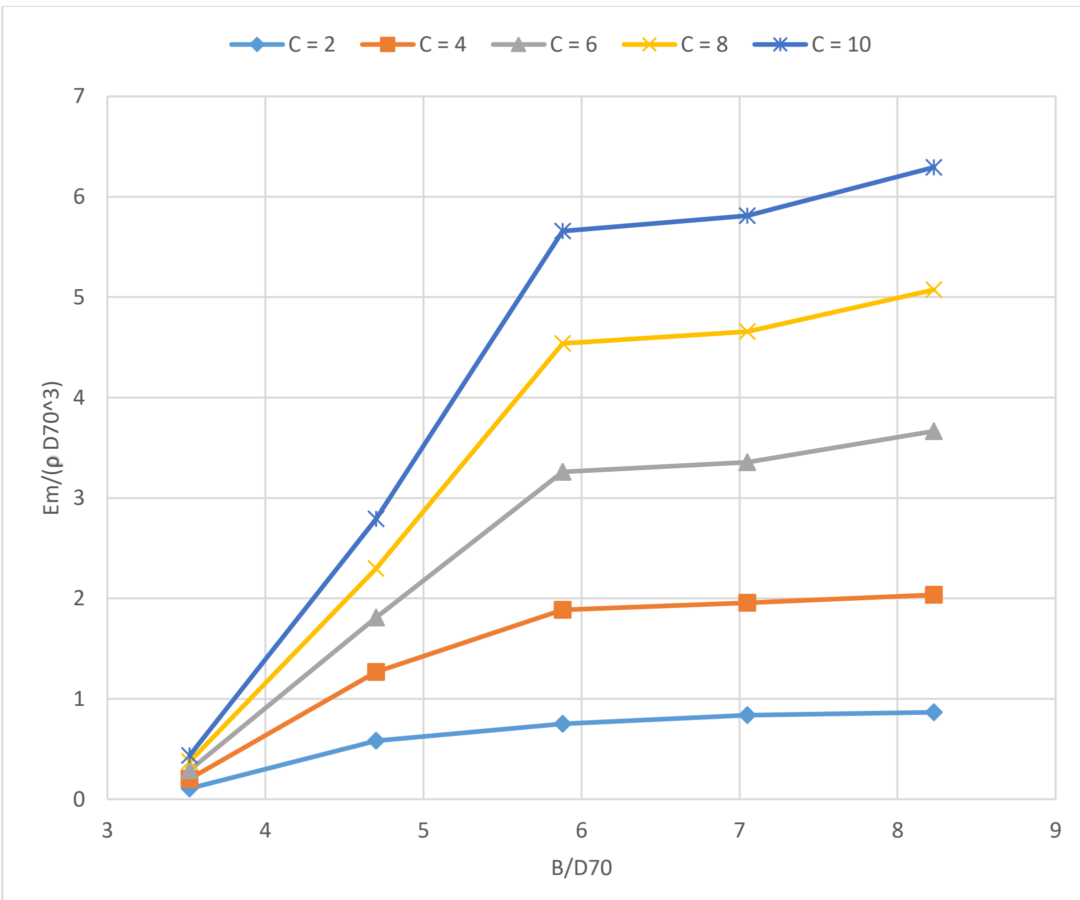


Figure 5-27 The effect of the ratio of leak width to soil particle size on the rate of erosion,($\frac{Hw}{D70}$ = 13.52, W=0%)

Fig. (5-28) shows the effect of the ratio between the height of water in the soil and the soil paricle size ($H_w/D_{70}$). The relation is positive, the correlation value is 0.62. Higher water level means more water spread in the soil and thus more soil becomes disturbed and able to leave with water. Furthermore, higher water level applies more pressure on the leakage and pushes more soil into the pipe.

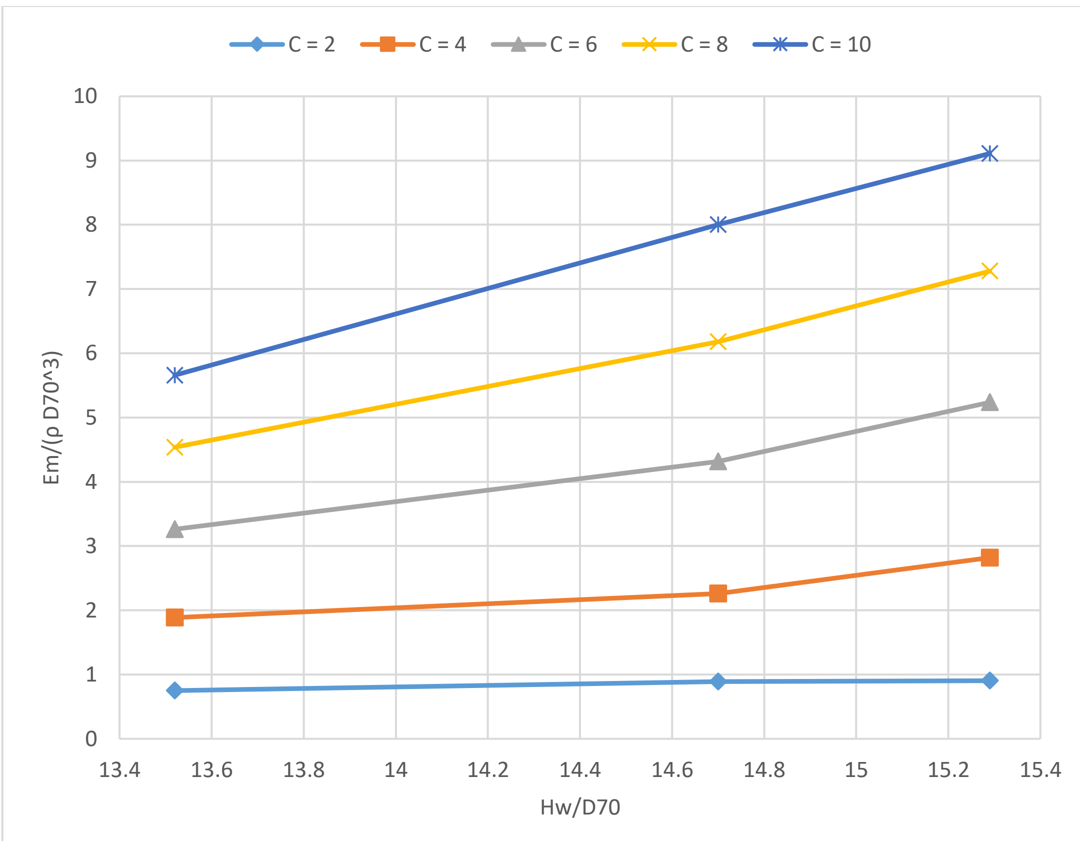


Figure 5-28 The effect of the height of water in soil on the rate of erosion, ($\frac{B}{D70} = 5.88, W = 0$)

Fig (5-29) shows the effect of initial water content on the rate of erosion. The effect is limited compared to the leakage width. The relation is positive, the correlation value is 0.6 .

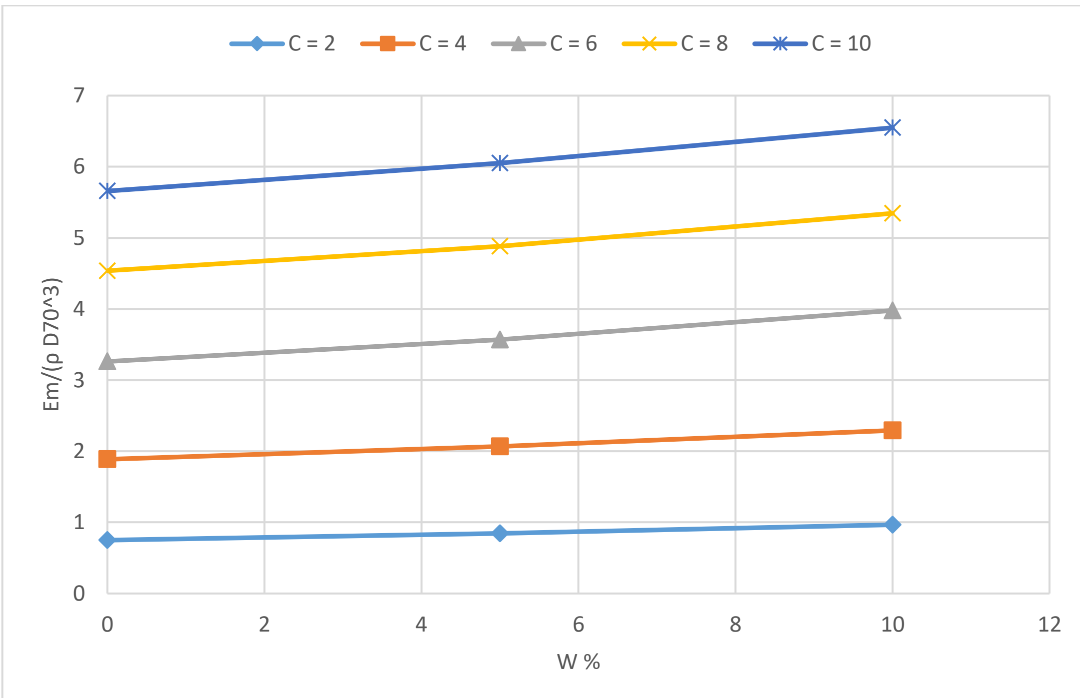


Figure 5-29 The "effect of initial water content" on the rate of erosion

Fig (5-30) shows the effect of different water flow rates on the rate of soil erosion. Based on the limitations of the experimental tests, it can be found that water flow rate has no noticeable effect on the rate of soil erosion. Previous studies were shown that the value of water flow rate through the leakage is important in the case of continuous sewer or water pipe exfiltration, while the present study focused on cyclic water flow.

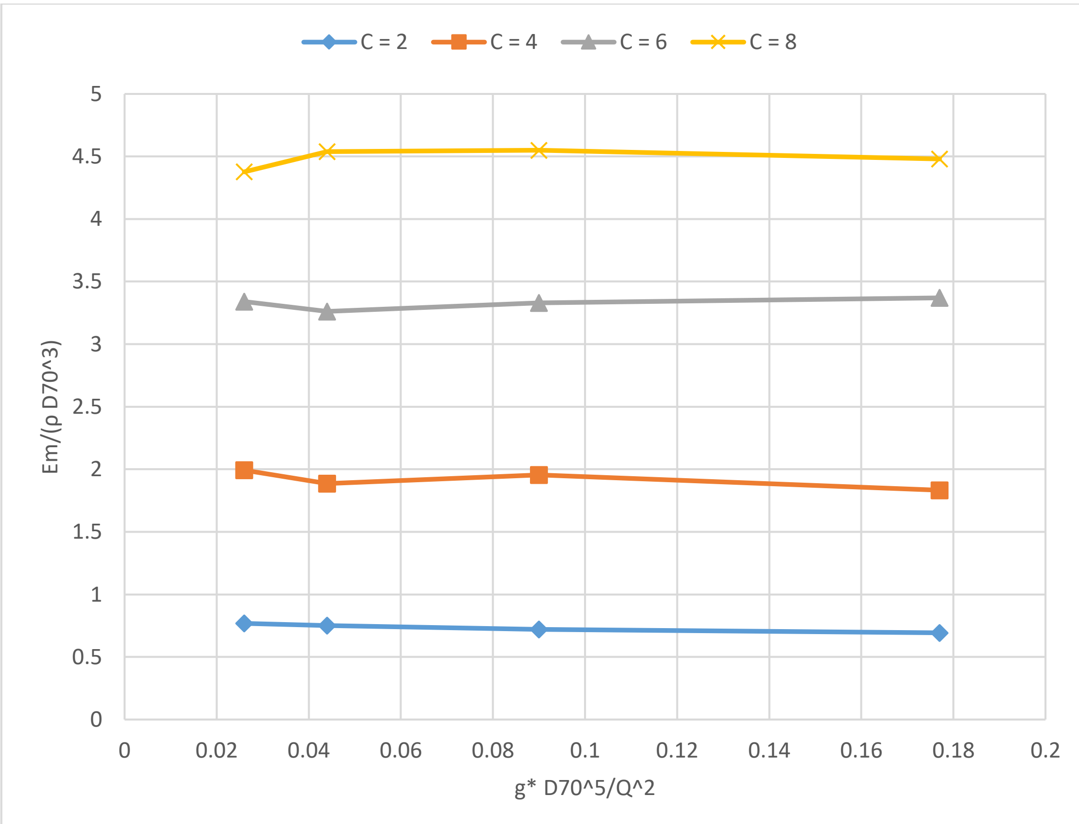


Figure 5-30 The effect of water flow rate value on the erosion

SPSS software was carried out to achieve the analysis and build the required model. The prediction model was linear, and the analysis results of the model is shown in Tables (5-3, 4, 5 and 6). The other 67 data sets was used to validate the proposed dimensionless model. Fig. (5-31) presents the comparison between the experimental data and the estimated values of the rate of soil erosion. Value of coefficient of determination was of ($R^2$ = 0.864). It can be concluded that the rate of erosion for the local sandy soil under similar conditions can be reasonably estimated using the dimensional analysis.

Table 5-3 Prediction Model

| Linear regression | |
|---|---|
| Developed model | $\frac{Em}{\rho\, D70^3}$ = -0.524 – 0.905 ( C + CW) + 0.063 ( C * $\frac{Hw}{D70}$ * LN( $\frac{B}{D70}$ )) |

Table 5-4 Model Summary

**Model Summary**

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate |
|---|---|---|---|---|
| 1 | .935[a] | .874 | .873 | .8620900 |

a. Predictors: (Constant), CHLN(B), CW

Table 5-5 The Coefficients Estimation

**Coefficients[a]**

| Model | | Unstandardized Coefficients B | Unstandardized Coefficients Std. Error | Standardized Coefficients Beta | t | Sig. |
|---|---|---|---|---|---|---|
| 1 | (Constant) | -.524 | .135 | | -3.884 | .000 |
| | CW | -.905 | .057 | -1.065 | -15.956 | .000 |
| | CHLN(B) | .063 | .002 | 1.819 | 27.239 | .000 |

a. Dependent Variable: Es

Table 5-6 ANOVA Index

**ANOVA[a]**

| Model | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| 1 | Regression | 958.777 | 2 | 479.388 | 645.034 | .000[b] |
| | Residual | 138.235 | 186 | .743 | | |
| | Total | 1097.012 | 188 | | | |

a. Dependent Variable: Es

b. Predictors: (Constant), CHLN(B), CW

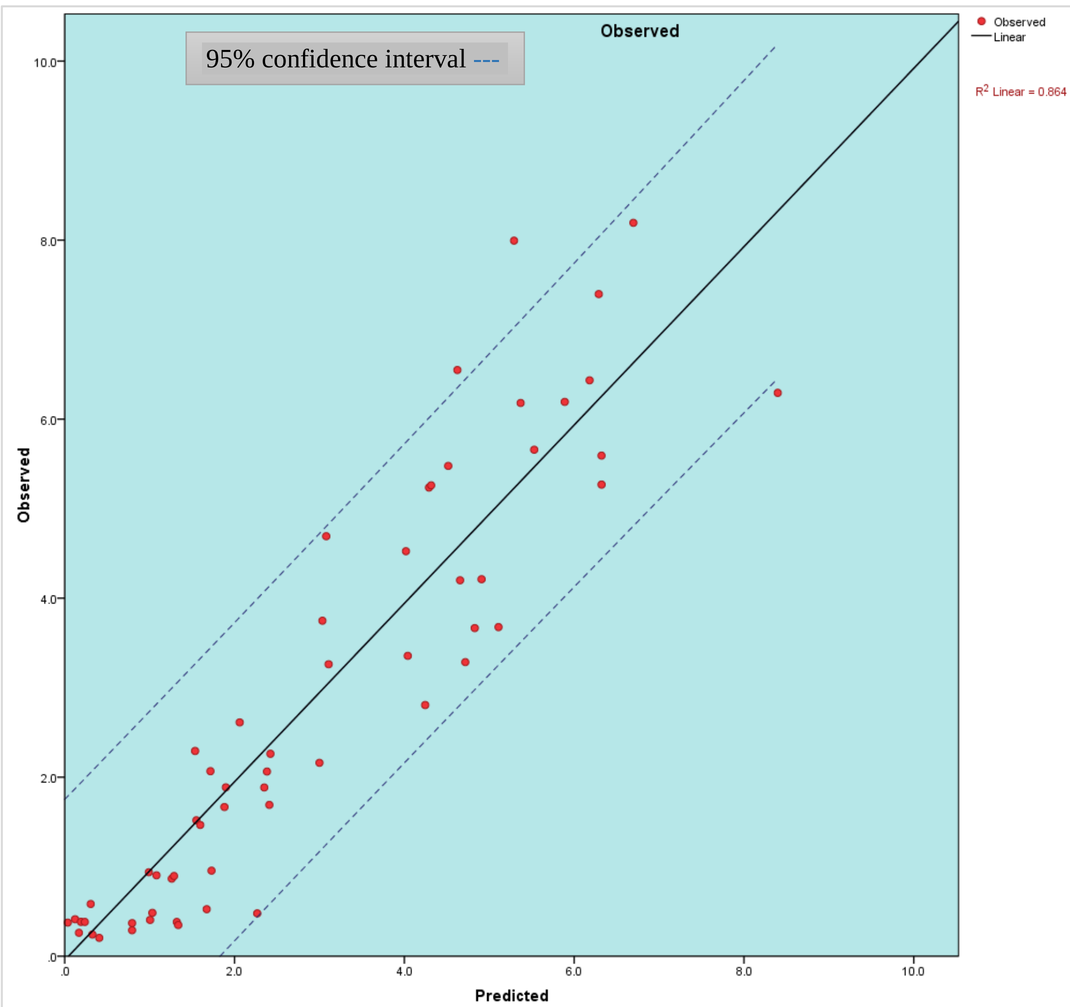


Figure 5-31 coparisons between the exprimental and predicted values  of the rate of erosion

# Chapter Six

## Conclusions and Recommendations

### 6.1 Conclusions

The present study was investigated the mechanisms of soil erosion induced by defective sewer pipes. Using local sandy soil and local sewer pipe embedment material. Soil near sewer pipe defect can be eroded as the water flow in exfiltration/infiltration cycles through the pipe defect, which can cause soil loss and finally leads to sinkhole formation. Experimental tests were conducted, and an experimental model was builded to simulate the soil erosion process. From the experimental data analysis, a dimensionless pridiction model were developed to estimate the rate of soil erosion. Generally, conclusions of the present study can be summarized as follows:

1- The exfiltration/infiltration process through sewer pipe defects leads to soil erosion and cavity formation. Cavities are often formed from the third cycle and expanded with increasing number of cycles.

2- Local sandy soils are sensitive to erosion due to its small size of granules, their ease of movement with water and their sensitivity to water exfiltration/infiltration cycles.

3- It was found that both leakage width as well as soil particle size have significant effects on the amount of soil draining into the sewer pipe, where the amount of collected eroded soil is inversely proportional to the ratio of soil particle size to leakage size. The results of the experiments and data analysis showed that the ratio of $B/D_{70}$ is the most influential factor on soil erosion among the other factors. Where: 7mm of leakage width has 14.5 times, 6mm has 13.4 times, 5mm has 13 times and 4mm has 6.4 times of eroded soil mass compared to the amount of eroded soil mass collected through the leakage width of 3mm.

4- When the ratio of $D_{70}/B$ is less than 0.17, the eroded soil drains through the pipe leakage easily and continuously.

5- In terms of experimental sandy soil, particle sizes less than $0.42_{mm}$ are more prone to erosion and larger sizes are more resistant. While particle sizes less than 0.3mm were more prone to erosion in the subbase of type (D) .

6- The results showed that the importance of the relative density of soil in erosion resistance, where the amount of eroded soil increased when the soil has the relative density less than 80%. The vertical movement of soil particles was greater when the relative density less than 80%.

7- High level of water in the soil causes the widening of the cavity quickly and increase the rate of erosion. The amount of eroded soil mass increased by 40% for each 10% increment in the height of water (Hw). Also, the cavity ceiling began to collapse when the water level rose above it.

8- High initial water content of the soil leads to an increase in soil erosion and an increase in the formation of weak areas around the cavity. It was found that soil with 5% of initial water content has 7% more amount of eroded soil mass, while soil with 10% of initial water content has 16% more amount of eroded soil mass.

9- PIV technique was effectively implemented in this study to evaluate the failure mechanism due to soil migration near to and far from a pipe defect. Ground displacement troughs due to arching effects can be evaluated at any place and at any cycle of the testing process based on image correlation.

10- By observing the vertical displacement of the soil layers, it becomes apparent that the amount of the drop increases as the layer approaches the defect or the cavity and decreases the closer the layer is to the soil surface.

11- The results showed that the subbase type(D) is more resistant to erosion than the local soil. Subbase was more resistant at rate of (50-90%) for different leakage sizes and by 19% for the change in volume of water inflow. It reduces erosion and increases the chances of clogging the leakage because it contains more of the clay, larger size of particles and lack of water permeability .

12- It was found that the proposed dimensional analysis prediction model can reasonably estimate the rate of erosion for the local sandy soil. The value of coefficient of determination was of ($R^2 = 0.873$) .

## 6.2 Recommendation for future studies

In order to obtain an increase in the informations on soil behavior with defective sewer pipe, the study of the soil erosion on a larger scale would increase the chances of more understanding of the phenomenon of soil erosion.

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# APPENDIX - A

## Case Studies of Sinkholes induced by defective sewer pipes

In terms of sinkholes accidents, a small number of studies focused on this issues, and that is because sinkholes accidents often occur without any prior warning or signs. Information about sinkhole accidents were gathered from news reports are shown in Table A-1. These reports can help us in the investigation and analysis of sinkhole accidents. In the present study, the terminology of sinkhole refers to that kind of sinkholes which formed by soil erosion in the urban areas by defective pipes.

Table A-1 Sinkhole accidents induced by defective sewer pipes

| Time | Location | Water condition | Type of soil | Pipe condition and possible cause | Consequence | |
|---|---|---|---|---|---|---|
| | | | | | Sinkhole size (diameter, depth) | Loss |
| 06/1993 | Georgia, US | Heavy storm | Soil and construction rubble | A sewer tunnel with a diameter of 4 m failure, soil erosion | 20 m, 10 m | 2 killed |
| 02/2007 | Guatermala | Heavy storm | Pumice and volcanic ash | Overloaded sewer or drainage pipe with a diameter of 3.75-4.50 m | 20 m, 60 m | 3 killed |
| 09/2009 | Toronto,Canada | Heavy rainfall | - | - | 5 m, 14 m | - |
| 06/2010 | Guatermala | Heavy storm | Pumice and volcanic ash | Overloaded sewer or drainage pipe with a diameter of 3.75-4.50 m | 18 m, 30 m | 152 killed |
| 09/2010 | Texas, US | Not reported but near a lake | Sandy soil | A pipe with a diameter of 1.2m failure | 2 m diameter | - |
| 01/2011 | Austin, Texas, US | - | - | Soil erosion into the storm sewer pipe | 2.7 m deep | - |
| 02/2011 | Florida, US | - | - | Corroded sewer line | 1.5 m, 4 m | - |
| 03/2011 | Ohio, US | Heavy rainfall | - | A defective 60-year-old sewer pipe, soil was washed away | - | - |
| 03/2011 | Connecticut,US | - | - | broken sewer line | 5 m deep | - |
| 03/2011 | New South Wales,Australia | Heavy rainfall | - | Soil erosion into the sewer pipe | 8 m, 6 m | - |
| 04/2011 | Saskatoon, Canada | Freezing | - | Broken sewer line due to freezing | 3 m deep | - |
| 04/2011 | New York, US | Storm | - | 199-year-old clay sewer pipe | 9 m, 6 m | $4.5 million |

Table A-1 Sinkhole accidents induced by defective sewer pipes continued 1

| Time | Location | Water condition | Type of soil | Pipe condition and possible cause | Consequence | |
|---|---|---|---|---|---|---|
| | | | | | Sinkhole size (diameter, depth) | Loss |
| 05/2011 | Ohio, US | - | - | Collapsed brick sewer line | 4 m deep | - |
| 05/2011 | New Jersey, US | - | - | Collapsed sewer line | 10 m , 1.5 m | - |
| 06/2011 | New York, US | Steady rain for a month | Sandy soil | Broken clay sewer pipe, soil loss | - | - |
| 06/2011 | Ohio, US | - | - | Soil erosion into an 84-year-old brick tunnel with a diameter of 1 m | 5 m deep | - |
| 08/2011 | Pennsylvania, US | Extreme wet weather event, hurricane | Backfill granular material | A corrugated metal pipe with a diameter of 2.1 m deteriorated | 2 m wide | $263,000 |
| 04/2012 | Bangkok, Thailand | - | Sand | Soil erosion into the broken drainage pipe | 1 m, 1 m | - |
| 09/2012 | Ottawa, Canada | Heavy rainfall | - | Soil loss into a 3.6 m wide storm sewer pipe | - | One car |
| 09/2012 | Shanghai, China | - | Sandy soil | Sewer pipe beneath | 3.5 m, 1.5 m | - |
| 04/2013 | Chicago, US | Heavy storm | - | Defective sewer line, soil loss | 3 m in diameter | - |
| 05/2013 | Ontario, Canada | Increasing height of nearby river | Granular material | Soil erosion into the storm sewer pipe | Small sinkholes | - |
| 05/2014 | Edmonton, Canada | Rainfall | - | Drainage issue | - | - |
| 05/2014 | Minnesota, US | - | - | Broken sanitary sewer pipe | - | $2 million |
| 01/2015 | Scotland, UK | - | Sand | Drainage issue | 4 m deep | $ 30,000 |
| 04/2015 | Mississippi, US | - | - | Soil erosion into the culvert buried 9.5 m below ground | 3 m diameter | - |

Table A-1 Sinkhole accidents induced by defective sewer pipes continued 2

| Time | Location | Water condition | Type of soil | Pipe condition and possible cause | Consequence | |
|---|---|---|---|---|---|---|
| | | | | | Sinkhole size (diameter, depth) | Loss |
| 11/2015 | Ohio, US | Heavy rainfall | - | Soil erosion into the defective sewer pipes | 1.5 m, 1 m | - |
| 04/2016 | California, US | Heavy rainfall | - | Sewer pipe collapsed, soil erosion | 5 m deep | - |
| 04/2016 | Hangzhou, China | Heavy rainfall | Sand | Soil erosion into the defective storm pipe | 2.5 m, 2 m | - |
| 06/2016 | Ottawa, Canada | - | - | Soil erosion into defective pipes | 28 m wide, 40 m long, 5 m deep | - |
| 07/2016 | Beijing, China | Heavy rainfall | - | Soil erosion and fluidization due to the defective pipes | 20 m long, 5 m wide, 1.5 m deep | - |
| 08/2016 | Cambridge, UK | - | - | Erosion into the defective pipes | 4 m deep | - |
| 08/2016 | Kentucky, US | Heavy rainfall | - | Defective sewer pipes | 0.6 m, 1.8 m | - |
| 11/2016 | Likas, Malaysia | Earthquake | - | Cracked sewer pipe | 1.5 m, 1.8 m | - |
| 11/2016 | Fukuoka, Japan | - | Sand | Erosion into tunnel, defective sewer pipe | 30 m long, 27 m wide, 15 m deep | - |
| 11/2016 | Shenzhen, China | - | - | Erosion into defective sewer pipes 4 m below the ground | 3 m, 2 m | - |
| 01/2017 | Michigan, US | - | - | Soil erosion and collapsed pipe 15 m below the ground | Football field-sized | 22 families moved |

In general, the formation of sinkhole caused by defective sewer pipes can be explained by a scheme, depending on the information and descriptions received from these incidents as shown in Fig. (A-1). When the buried pipes start to age and deteriorate, cracks, openings and other defects starts to appear and increase. If the groundwater table is higher than the defected sewer pipe, soil near the defect will erode and migrate into the defective sewer pipe with water. Furthermore, if the sewer pipe is fully filled ,the water in pipe will exfiltrate through the defects and this lead to fluidization and erosion of adjacent soils. With continued soil loss through the pipe defect, soil could form an arch which can limit the extent of the erosion if it was stable. The ground collapse can occur due to the instability induced by more of soil erosion , heavy rain storming , high water table or heavy traffic loads.

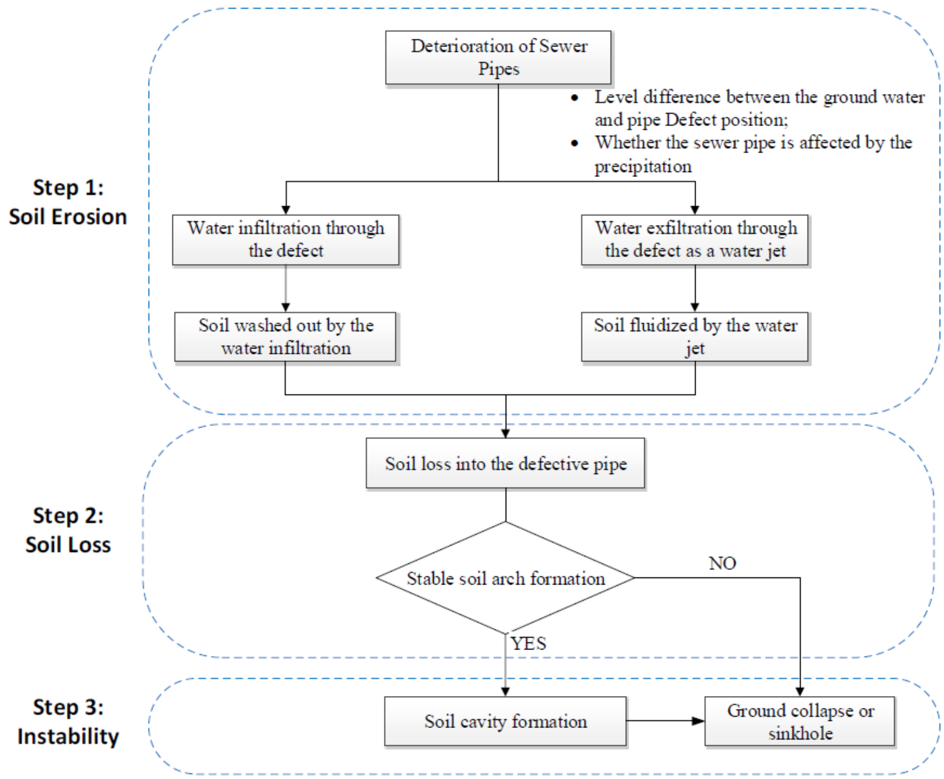


Figure A-1 Conceptualmodel of sinkhole creation caused by defective sewer pipe

(Kim and Kim, 2018), described the stages which generally lead to the formation of sinkholes due to soil erosion through defective sewer pipes in a sewer system. They explained that the groundwater level ascends when it  rains heavily. In the meantime, the stormwater and the sewage water are filling the sewers and may exfiltrate from the sewer pipe through the defects which, disturb the surrounding soil and leads to the fluidization of it (Fig. A-2a, b). When the rain stops, the level of groundwater will decrease, accompanied by the migration of the irritated soil granules into the sewer pipe through the pipe defects, the repetition of this process leads to the creation of a cavity, the ground cavity gradually expands and eventually form a sinkhole, as shown in Fig. (A-2c). The pavement above the enlarged cavity fails because various overloads such as traffic loads Fig. (A-2d).

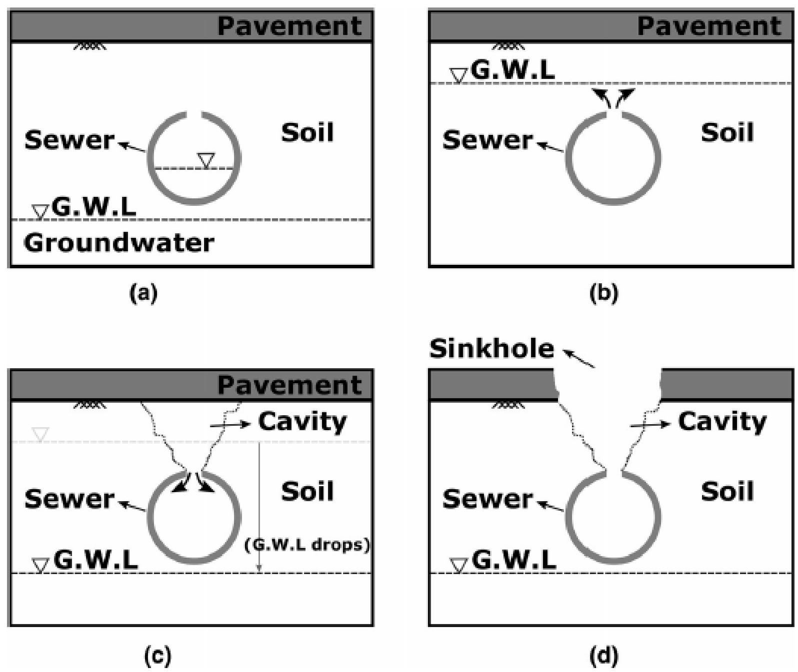


Figure 0-1 sinkhole formation stages due to defective sewer pipe (a) before the rain (b) during the rain, (Kim and Kim, 2018)

The sinkhole problem leads to progressively severe consequences. From the accidents in Table (A-1), and as the majority of the accidents happened in popular urban area, the remediation process cost millions of dollars. In addition, rehabilitation processes are very difficult and the direct consequence is severe. Furthermore, there are other incidental costs such as, damage of nearby services and the interception of transport and many other issues (Davies et al., 2001) . The most dangerous concern is the loss of human life, where sinkhole often happened in the populated urban areas.

the major reason why sinkhole accidents are occurred, because of the change in the water condition. Where water situation can be influenced by different parameters. Soil particles may be washed out into the pipe through the defect due to an increase in the water level caused by heavy rainfall. Table A-1, shows that most of the accidents on US eastern coast in 2011 were due to the severe hurricanes. The failures in Texas, US (2010) and Ontario, Canada (2013) were occurred near the lake or river particularly, when the groundwater situation was influenced by the water height in the lake or river. The freeze damaged the sewer pipe, however melting initiated a fast rise in water level in Saskatoon, Canada (2011).

It can be deduced from the mentioned cases that the deterioration of sewer pipe is the key condition for sinkhole development. Defects can appear in the sewer pipe due to different reasons such as, internal pressure, corrosion and applied loads (Makar, 2000) . Some of the aged sewer networks were built using brick tunnel or clay pipes, which will easily to deteriorate leading to soil erosion and even can develope to sinkhole accident (New York US, 2011; Ohio, US, 2011) .

Sinkhole and roads subsidence accidents frequently happen in sandy soils. From studies by (WRC, 2001)(Water Research Center) as shown in Table A-2, soils that have slight or no cohesion are very easy to disturb and can be easily washed out by water.

Table A-2 The ground loss affected by different types of soils (WRC,2001)

| Soil type | Risk of ground loss |
|---|---|
| | High ↑ |
| Silts, silty fine sands or fine sands | |
| Medium to coarse sands | |
| Low plasticity clays (plasticity index < 15) | |
| Fine to medium gravels | |
| Well grade sandy gravels | |
| Medium to high plasticity clays (plasticity index > 15) | |
| All clays if sewer constructed by tunnelling | |
| | ↓ Low |

## Sources of Urban Sinkholes in Table (A-1)


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# APPENDIX - B

The experimental data :

| | Em/(ρ D70^3) | B/D70 | Hw/D70 | C | W |
|---|---|---|---|---|---|
| 1 | 0.0567774 | 3.529412 | 13.52941 | 1 | 1 |
| 2 | 0.166047115 | 3.529412 | 13.52941 | 3 | 1 |
| 3 | 0.21318307 | 3.529412 | 13.52941 | 4 | 1 |
| 4 | 0.304241165 | 3.529412 | 13.52941 | 6 | 1 |
| 5 | 0.350305848 | 3.529412 | 13.52941 | 7 | 1 |
| 6 | 0.393156716 | 3.529412 | 13.52941 | 8 | 1 |
| 7 | 0.457433019 | 3.529412 | 13.52941 | 10 | 1 |
| 8 | 0.127481333 | 3.529412 | 14.70588 | 2 | 1 |
| 9 | 0.196042722 | 3.529412 | 14.70588 | 3 | 1 |
| 10 | 0.254962666 | 3.529412 | 14.70588 | 4 | 1 |
| 11 | 0.358876022 | 3.529412 | 14.70588 | 6 | 1 |
| 12 | 0.444577758 | 3.529412 | 14.70588 | 8 | 1 |
| 13 | 0.498141344 | 3.529412 | 14.70588 | 9 | 1 |
| 14 | 0.523851865 | 3.529412 | 14.70588 | 10 | 1 |
| 15 | 0.074989019 | 3.529412 | 15.29412 | 1 | 1 |
| 16 | 0.145692952 | 3.529412 | 15.29412 | 2 | 1 |
| 17 | 0.268889198 | 3.529412 | 15.29412 | 4 | 1 |
| 18 | 0.310668795 | 3.529412 | 15.29412 | 5 | 1 |
| 19 | 0.416724694 | 3.529412 | 15.29412 | 7 | 1 |
| 20 | 0.463860649 | 3.529412 | 15.29412 | 8 | 1 |
| 21 | 0.528136951 | 3.529412 | 15.29412 | 10 | 1 |
| 22 | 0.053563585 | 3.529412 | 13.52941 | 1 | 1.1 |
| 23 | 0.172474745 | 3.529412 | 13.52941 | 3 | 1.1 |
| 24 | 0.222824515 | 3.529412 | 13.52941 | 4 | 1.1 |
| 25 | 0.32031024 | 3.529412 | 13.52941 | 6 | 1.1 |
| 26 | 0.352448391 | 3.529412 | 13.52941 | 7 | 1.1 |
| 27 | 0.381372728 | 3.529412 | 13.52941 | 8 | 1.1 |
| 28 | 0.425294868 | 3.529412 | 13.52941 | 10 | 1.1 |
| 29 | 0.154263126 | 3.529412 | 14.70588 | 2 | 1.1 |

| | | | | | |
|---|---|---|---|---|---|
| 30 | 0.224967058 | 3.529412 | 14.70588 | 3 | 1.1 |
| 31 | 0.338521859 | 3.529412 | 14.70588 | 5 | 1.1 |
| 32 | 0.393156716 | 3.529412 | 14.70588 | 6 | 1.1 |
| 33 | 0.453147932 | 3.529412 | 14.70588 | 7 | 1.1 |
| 34 | 0.486357355 | 3.529412 | 14.70588 | 8 | 1.1 |
| 35 | 0.528136951 | 3.529412 | 14.70588 | 10 | 1.1 |
| 36 | 0.082487921 | 3.529412 | 15.29412 | 1 | 1.1 |
| 37 | 0.230323417 | 3.529412 | 15.29412 | 3 | 1.1 |
| 38 | 0.283887002 | 3.529412 | 15.29412 | 4 | 1.1 |
| 39 | 0.335308044 | 3.529412 | 15.29412 | 5 | 1.1 |
| 40 | 0.45207666 | 3.529412 | 15.29412 | 7 | 1.1 |
| 41 | 0.492784985 | 3.529412 | 15.29412 | 8 | 1.1 |
| 42 | 0.525994408 | 3.529412 | 15.29412 | 9 | 1.1 |
| 43 | 0.361018565 | 5.882353 | 13.52941 | 1 | 1 |
| 44 | 0.789527248 | 5.882353 | 13.52941 | 2 | 1 |
| 45 | 1.34337472 | 5.882353 | 13.52941 | 3 | 1 |
| 46 | 2.640684757 | 5.882353 | 13.52941 | 5 | 1 |
| 47 | 4.145821505 | 5.882353 | 13.52941 | 7 | 1 |
| 48 | 4.77680054 | 5.882353 | 13.52941 | 8 | 1 |
| 49 | 5.365999979 | 5.882353 | 13.52941 | 9 | 1 |
| 50 | 0.428508683 | 5.882353 | 14.70588 | 1 | 1 |
| 51 | 0.939505287 | 5.882353 | 14.70588 | 2 | 1 |
| 52 | 1.552272703 | 5.882353 | 14.70588 | 3 | 1 |
| 53 | 3.342367725 | 5.882353 | 14.70588 | 5 | 1 |
| 54 | 4.543263308 | 5.882353 | 14.70588 | 6 | 1 |
| 55 | 5.541688538 | 5.882353 | 14.70588 | 7 | 1 |
| 56 | 7.460336165 | 5.882353 | 14.70588 | 9 | 1 |
| 57 | 8.424480701 | 5.882353 | 14.70588 | 10 | 1 |
| 58 | 0.431722498 | 5.882353 | 15.29412 | 1 | 1 |
| 59 | 1.860798954 | 5.882353 | 15.29412 | 3 | 1 |
| 60 | 2.967422627 | 5.882353 | 15.29412 | 4 | 1 |
| 61 | 4.410425616 | 5.882353 | 15.29412 | 5 | 1 |
| 62 | 6.589392268 | 5.882353 | 15.29412 | 7 | 1 |
| 63 | 7.660663974 | 5.882353 | 15.29412 | 8 | 1 |
| 64 | 9.588953046 | 5.882353 | 15.29412 | 10 | 1 |
| 65 | 0.888084245 | 5.882353 | 13.52941 | 2 | 1.05 |
| 66 | 1.435504087 | 5.882353 | 13.52941 | 3 | 1.05 |
| 67 | 2.908502684 | 5.882353 | 13.52941 | 5 | 1.05 |
| 68 | 3.756949875 | 5.882353 | 13.52941 | 6 | 1.05 |

| | | | | | |
|---|---|---|---|---|---|
| 69 | 4.471488104 | 5.882353 | 13.52941 | 7 | 1.05 |
| 70 | 5.137819105 | 5.882353 | 13.52941 | 8 | 1.05 |
| 71 | 6.368710296 | 5.882353 | 13.52941 | 10 | 1.05 |
| 72 | 0.41458215 | 5.882353 | 14.70588 | 1 | 1.05 |
| 73 | 0.955574362 | 5.882353 | 14.70588 | 2 | 1.05 |
| 74 | 2.401791166 | 5.882353 | 14.70588 | 4 | 1.05 |
| 75 | 3.365935702 | 5.882353 | 14.70588 | 5 | 1.05 |
| 76 | 4.466131745 | 5.882353 | 14.70588 | 6 | 1.05 |
| 77 | 6.513331976 | 5.882353 | 14.70588 | 8 | 1.05 |
| 78 | 7.46354998 | 5.882353 | 14.70588 | 9 | 1.05 |
| 79 | 0.433865041 | 5.882353 | 15.29412 | 1 | 1.05 |
| 80 | 1.69475184 | 5.882353 | 15.29412 | 3 | 1.05 |
| 81 | 2.563553194 | 5.882353 | 15.29412 | 4 | 1.05 |
| 82 | 3.634824901 | 5.882353 | 15.29412 | 5 | 1.05 |
| 83 | 5.857713692 | 5.882353 | 15.29412 | 7 | 1.05 |
| 84 | 6.821858228 | 5.882353 | 15.29412 | 8 | 1.05 |
| 85 | 0.428508683 | 5.882353 | 13.52941 | 1 | 1.1 |
| 86 | 1.017708121 | 5.882353 | 13.52941 | 2 | 1.1 |
| 87 | 1.66368496 | 5.882353 | 13.52941 | 3 | 1.1 |
| 88 | 3.324156106 | 5.882353 | 13.52941 | 5 | 1.1 |
| 89 | 4.188672373 | 5.882353 | 13.52941 | 6 | 1.1 |
| 90 | 5.626319003 | 5.882353 | 13.52941 | 8 | 1.1 |
| 91 | 6.261583125 | 5.882353 | 13.52941 | 9 | 1.1 |
| 92 | 1.115193847 | 5.882353 | 14.70588 | 2 | 1.1 |
| 93 | 1.892937106 | 5.882353 | 14.70588 | 3 | 1.1 |
| 94 | 3.858720687 | 5.882353 | 14.70588 | 5 | 1.1 |
| 95 | 5.037119565 | 5.882353 | 14.70588 | 6 | 1.1 |
| 96 | 6.238015148 | 5.882353 | 14.70588 | 7 | 1.1 |
| 97 | 7.344638821 | 5.882353 | 14.70588 | 8 | 1.1 |
| 98 | 0.447791573 | 5.882353 | 15.29412 | 1 | 1.1 |
| 99 | 1.075556793 | 5.882353 | 15.29412 | 2 | 1.1 |
| 100 | 1.898293464 | 5.882353 | 15.29412 | 3 | 1.1 |
| 101 | 2.767094818 | 5.882353 | 15.29412 | 4 | 1.1 |
| 102 | 5.123892573 | 5.882353 | 15.29412 | 6 | 1.1 |
| 103 | 6.47798001 | 5.882353 | 15.29412 | 7 | 1.1 |
| 104 | 7.748508254 | 5.882353 | 15.29412 | 8 | 1.1 |
| 105 | 0.385657814 | 8.235294 | 13.52941 | 1 | 1 |
| 106 | 1.458000793 | 8.235294 | 13.52941 | 3 | 1 |
| 107 | 2.132901968 | 8.235294 | 13.52941 | 4 | 1 |

| | | | | | |
|---|---|---|---|---|---|
| 108 | 2.861366728 | 8.235294 | 13.52941 | 5 | 1 |
| 109 | 4.634321403 | 8.235294 | 13.52941 | 7 | 1 |
| 110 | 5.340289458 | 8.235294 | 13.52941 | 8 | 1 |
| 111 | 6.000192829 | 8.235294 | 13.52941 | 9 | 1 |
| 112 | 0.416724694 | 8.235294 | 14.70588 | 1 | 1 |
| 113 | 0.952360547 | 8.235294 | 14.70588 | 2 | 1 |
| 114 | 1.620834092 | 8.235294 | 14.70588 | 3 | 1 |
| 115 | 2.475708914 | 8.235294 | 14.70588 | 4 | 1 |
| 116 | 4.650390479 | 8.235294 | 14.70588 | 6 | 1 |
| 117 | 5.721662185 | 8.235294 | 14.70588 | 7 | 1 |
| 118 | 6.782221175 | 8.235294 | 14.70588 | 8 | 1 |
| 119 | 7.853492881 | 8.235294 | 14.70588 | 9 | 1 |
| 120 | 0.437078856 | 8.235294 | 15.29412 | 1 | 1 |
| 121 | 1.768669588 | 8.235294 | 15.29412 | 3 | 1 |
| 122 | 2.769237362 | 8.235294 | 15.29412 | 4 | 1 |
| 123 | 5.175313615 | 8.235294 | 15.29412 | 6 | 1 |
| 124 | 6.375137926 | 8.235294 | 15.29412 | 7 | 1 |
| 125 | 7.509614664 | 8.235294 | 15.29412 | 8 | 1 |
| 126 | 0.415653422 | 8.235294 | 13.52941 | 1 | 1.1 |
| 127 | 0.940576558 | 8.235294 | 13.52941 | 2 | 1.1 |
| 128 | 2.621401866 | 8.235294 | 13.52941 | 4 | 1.1 |
| 129 | 3.536267904 | 8.235294 | 13.52941 | 5 | 1.1 |
| 130 | 4.593613078 | 8.235294 | 13.52941 | 6 | 1.1 |
| 131 | 5.571684146 | 8.235294 | 13.52941 | 7 | 1.1 |
| 132 | 7.446409633 | 8.235294 | 13.52941 | 9 | 1.1 |
| 133 | 0.462789377 | 8.235294 | 14.70588 | 1 | 1.1 |
| 134 | 1.120550205 | 8.235294 | 14.70588 | 2 | 1.1 |
| 135 | 3.067050896 | 8.235294 | 14.70588 | 4 | 1.1 |
| 136 | 4.138322603 | 8.235294 | 14.70588 | 5 | 1.1 |
| 137 | 5.503122757 | 8.235294 | 14.70588 | 6 | 1.1 |
| 138 | 7.905985195 | 8.235294 | 14.70588 | 8 | 1.1 |
| 139 | 0.543134755 | 8.235294 | 15.29412 | 1 | 1.1 |
| 140 | 1.196610496 | 8.235294 | 15.29412 | 2 | 1.1 |
| 141 | 2.113619077 | 8.235294 | 15.29412 | 3 | 1.1 |
| 142 | 3.292017955 | 8.235294 | 15.29412 | 4 | 1.1 |
| 143 | 5.774154499 | 8.235294 | 15.29412 | 6 | 1.1 |
| 144 | 7.070393264 | 8.235294 | 15.29412 | 7 | 1.1 |
| 145 | 0.230323417 | 4.705882 | 13.52941 | 1 | 1 |
| 146 | 1.011280491 | 4.705882 | 13.52941 | 3 | 1 |

| | | | | | |
|---|---|---|---|---|---|
| 147 | 1.332662003 | 4.705882 | 13.52941 | 4 | 1 |
| 148 | 1.626190451 | 4.705882 | 13.52941 | 5 | 1 |
| 149 | 1.903649823 | 4.705882 | 13.52941 | 6 | 1 |
| 150 | 2.417860242 | 4.705882 | 13.52941 | 8 | 1 |
| 151 | 2.674965451 | 4.705882 | 13.52941 | 9 | 1 |
| 152 | 2.93742702 | 4.705882 | 13.52941 | 10 | 1 |
| 153 | 0.26996047 | 4.705882 | 14.70588 | 1 | 1 |
| 154 | 0.686685164 | 4.705882 | 14.70588 | 2 | 1 |
| 155 | 1.115193847 | 4.705882 | 14.70588 | 3 | 1 |
| 156 | 1.843658607 | 4.705882 | 14.70588 | 5 | 1 |
| 157 | 2.111476534 | 4.705882 | 14.70588 | 6 | 1 |
| 158 | 2.401791166 | 4.705882 | 14.70588 | 7 | 1 |
| 159 | 2.685678169 | 4.705882 | 14.70588 | 8 | 1 |
| 160 | 3.235240554 | 4.705882 | 14.70588 | 10 | 1 |
| 161 | 0.273174285 | 4.705882 | 15.29412 | 1 | 1 |
| 162 | 0.649190654 | 4.705882 | 15.29412 | 2 | 1 |
| 163 | 1.077699337 | 4.705882 | 15.29412 | 3 | 1 |
| 164 | 1.537274899 | 4.705882 | 15.29412 | 4 | 1 |
| 165 | 1.92079017 | 4.705882 | 15.29412 | 5 | 1 |
| 166 | 2.622473138 | 4.705882 | 15.29412 | 7 | 1 |
| 167 | 2.948139737 | 4.705882 | 15.29412 | 8 | 1 |
| 168 | 3.260951075 | 4.705882 | 15.29412 | 9 | 1 |
| 169 | 3.545909349 | 4.705882 | 15.29412 | 10 | 1 |
| 170 | 0.879514071 | 7.058824 | 13.52941 | 2 | 1 |
| 171 | 1.436575359 | 7.058824 | 13.52941 | 3 | 1 |
| 172 | 2.057912948 | 7.058824 | 13.52941 | 4 | 1 |
| 173 | 2.707103603 | 7.058824 | 13.52941 | 5 | 1 |
| 174 | 4.260447577 | 7.058824 | 13.52941 | 7 | 1 |
| 175 | 4.903210601 | 7.058824 | 13.52941 | 8 | 1 |
| 176 | 6.115890173 | 7.058824 | 13.52941 | 10 | 1 |
| 177 | 0.428508683 | 7.058824 | 14.70588 | 1 | 1 |
| 178 | 1.573698137 | 7.058824 | 14.70588 | 3 | 1 |
| 179 | 2.430715502 | 7.058824 | 14.70588 | 4 | 1 |
| 180 | 3.361650615 | 7.058824 | 14.70588 | 5 | 1 |
| 181 | 5.504194029 | 7.058824 | 14.70588 | 7 | 1 |
| 182 | 6.524044693 | 7.058824 | 14.70588 | 8 | 1 |
| 183 | 7.58246114 | 7.058824 | 14.70588 | 9 | 1 |
| 184 | 0.424223596 | 7.058824 | 15.29412 | 1 | 1 |
| 185 | 0.959859449 | 7.058824 | 15.29412 | 2 | 1 |

| | | | | | |
|---|---|---|---|---|---|
| 186 | 2.674965451 | 7.058824 | 15.29412 | 4 | 1 |
| 187 | 3.639109987 | 7.058824 | 15.29412 | 5 | 1 |
| 188 | 4.654675565 | 7.058824 | 15.29412 | 6 | 1 |
| 189 | 6.957909735 | 7.058824 | 15.29412 | 8 | 1 |

The other randomly selected data to validate the model:

| | Em/(ρD70^3) | B/D80 | Hw/D70 | C | W |
|---|---|---|---|---|---|
| 1 | 0.106859353 | 3.529412 | 13.52941 | 2 | 1 |
| 2 | 0.242214533 | 3.529412 | 13.52941 | 5 | 1 |
| 3 | 0.405047832 | 3.529412 | 13.52941 | 9 | 1 |
| 4 | 0.061062487 | 3.529412 | 14.70588 | 1 | 1 |
| 5 | 0.290046815 | 3.529412 | 14.70588 | 5 | 1 |
| 6 | 0.382658254 | 3.529412 | 14.70588 | 7 | 1 |
| 7 | 0.204559332 | 3.529412 | 15.29412 | 3 | 1 |
| 8 | 0.348056177 | 3.529412 | 15.29412 | 6 | 1 |
| 9 | 0.478322817 | 3.529412 | 15.29412 | 9 | 1 |
| 10 | 0.111947893 | 3.529412 | 13.52941 | 2 | 1.1 |
| 11 | 0.253409322 | 3.529412 | 13.52941 | 5 | 1.1 |
| 12 | 0.383675962 | 3.529412 | 13.52941 | 9 | 1.1 |
| 13 | 0.075310401 | 3.529412 | 14.70588 | 1 | 1.1 |
| 14 | 0.261550987 | 3.529412 | 14.70588 | 4 | 1.1 |
| 15 | 0.484429066 | 3.529412 | 14.70588 | 9 | 1.1 |
| 16 | 0.147567678 | 3.529412 | 15.29412 | 2 | 1.1 |
| 17 | 0.369428048 | 3.529412 | 15.29412 | 6 | 1.1 |
| 18 | 0.525137391 | 3.529412 | 15.29412 | 10 | 1.1 |
| 19 | 1.886830857 | 5.882353 | 13.52941 | 4 | 1 |
| 20 | 3.261754529 | 5.882353 | 13.52941 | 6 | 1 |
| 21 | 5.658457154 | 5.882353 | 13.52941 | 10 | 1 |
| 22 | 2.261347446 | 5.882353 | 14.70588 | 4 | 1 |
| 23 | 6.180541421 | 5.882353 | 14.70588 | 8 | 1 |
| 24 | 0.903724812 | 5.882353 | 15.29412 | 2 | 1 |
| 25 | 5.236108284 | 5.882353 | 15.29412 | 6 | 1 |
| 26 | 8.193568085 | 5.882353 | 15.29412 | 9 | 1 |
| 27 | 0.375534297 | 5.882353 | 13.52941 | 1 | 1.05 |
| 28 | 2.066965194 | 5.882353 | 13.52941 | 4 | 1.05 |
| 29 | 5.477305109 | 5.882353 | 13.52941 | 9 | 1.05 |

| | | | | | |
|---|---|---|---|---|---|
| 30 | 1.518420517 | 5.882353 | 14.70588 | 3 | 1.05 |
| 31 | 5.260533279 | 5.882353 | 14.70588 | 7 | 1.05 |
| 32 | 0.938326888 | 5.882353 | 15.29412 | 2 | 1.05 |
| 33 | 4.524730307 | 5.882353 | 15.29412 | 6 | 1.05 |
| 34 | 7.396702626 | 5.882353 | 15.29412 | 9 | 1.05 |
| 35 | 2.292896397 | 5.882353 | 13.52941 | 4 | 1.1 |
| 36 | 4.691634439 | 5.882353 | 13.52941 | 7 | 1.1 |
| 37 | 6.548951761 | 5.882353 | 13.52941 | 10 | 1.1 |
| 38 | 0.413189497 | 5.882353 | 14.70588 | 1 | 1.1 |
| 39 | 2.612456747 | 5.882353 | 14.70588 | 4 | 1.1 |
| 40 | 7.994097293 | 5.882353 | 14.70588 | 9 | 1.1 |
| 41 | 3.748219011 | 5.882353 | 15.29412 | 5 | 1.1 |
| 42 | 0.866069611 | 8.235294 | 13.52941 | 2 | 1 |
| 43 | 3.665784653 | 8.235294 | 13.52941 | 6 | 1 |
| 44 | 6.293507022 | 8.235294 | 13.52941 | 10 | 1 |
| 45 | 3.285161816 | 8.235294 | 14.70588 | 5 | 1 |
| 46 | 0.955627926 | 8.235294 | 15.29412 | 2 | 1 |
| 47 | 3.676979442 | 8.235294 | 15.29412 | 5 | 1 |
| 48 | 1.667005903 | 8.235294 | 13.52941 | 3 | 1.1 |
| 49 | 6.192753918 | 8.235294 | 13.52941 | 8 | 1.1 |
| 50 | 1.884795441 | 8.235294 | 14.70588 | 3 | 1.1 |
| 51 | 6.433950743 | 8.235294 | 14.70588 | 7 | 1.1 |
| 52 | 4.200081417 | 8.235294 | 15.29412 | 5 | 1.1 |
| 53 | 0.583146754 | 4.705882 | 13.52941 | 2 | 1 |
| 54 | 2.062894362 | 4.705882 | 13.52941 | 7 | 1 |
| 55 | 1.466517403 | 4.705882 | 14.70588 | 4 | 1 |
| 56 | 2.80582129 | 4.705882 | 14.70588 | 9 | 1 |
| 57 | 2.160594342 | 4.705882 | 15.29412 | 6 | 1 |
| 58 | 0.382658254 | 7.058824 | 13.52941 | 1 | 1 |
| 59 | 3.355383676 | 7.058824 | 13.52941 | 6 | 1 |
| 60 | 5.268674944 | 7.058824 | 13.52941 | 9 | 1 |
| 61 | 0.895583147 | 7.058824 | 14.70588 | 2 | 1 |
| 62 | 4.211276206 | 7.058824 | 14.70588 | 6 | 1 |
| 63 | 1.690413189 | 7.058824 | 15.29412 | 3 | 1 |
| 64 | 5.592306127 | 7.058824 | 15.29412 | 7 | 1 |
| 65 | 1.992632541 | 5.882353 | 13.52941 | 4 | 1 |
| 66 | 3.261755212 | 5.882353 | 13.52941 | 6 | 1 |
| 67 | 4.357991256 | 5.882353 | 13.52941 | 8 | 1 |

## الخلاصة

يتم الإبلاغ عن حوادث فشل الطرق بسبب ضهور التكهفات مراراً وتكراراً في جميع أنحاء العالم ، وقد لوحظ ان عملية "تآكل التربة" بالقرب من أنابيب الصرف الصحي المعيبة هي احد اهم الأسباب المحتملة للتكهفات. مثل هذه الحوادث تسببت في خسائر اقتصادية كبيرة ، وشكلت تهديدًا خطيرًا لحياة البشر. عندما تتسرب المياه إلى أنابيب الصرف الصحي من خلال الفتحات والشقوق وغيرها من العيوب ، يمكن أن تنتقل جسيمات التربة إلى أنابيب الصرف الصحي مع الماء مما يؤدي إلى تشكل تجاويف وفي النهاية إلى تكهفات كبيرة. بالإضافة إلى ذلك ، يؤدي ترشيح المياه من خلال العيوب إلى التربة إلى تمييع التربة بالقرب من أنابيب الصرف الصحي ، مما يؤدي بدوره إلى عملية تآكل التربة. ركزت الدراسة الحالية على آلية تآكل التربة عن طريق دورة الترشيح / تسرب المياه من خلال العيب في الأنابيب وباستخدام التحليل البعدي لتطوير نموذج قياسي يتنبئ بتآكل التربة المحلية.

وأجريت التجارب باستخدام اختبارات نموذجية لمحاكاة تآكل التربة من خلال أنبوب صرف مجاري ، حيث اشتمل النموذج التجريبي على تربة تعرضت للتدفق الدوري للمياه من خلال تسرب يقع عند تاج الأنبوب. تم إجراء اختبارات النماذج تحت مصفوفة مختلفة من العوامل المؤثرة التي تؤثر على محفزات التآكل مثل: (1) حجم التسرب (2) توزيع حجم جسيمات التربة (3) الكثافة الجافة للتربة (4) المحتوى المائي الأولي (5) ارتفاع مستوى المياه في التربة (6) معدل التدفق خلال تسرب و (7) عدد الدورات. حيث تم جمع التربة المتآكلة وتجفيفها وترقيمها ونخلها لكل دورة. لوحظت عملية تكوين التجويف وتقييمها أثناء الاختبارات تحت ظروف التربة المختلفة. بحثت الدراسة الحالية عن هبوط طبقات التربة الناجمة عن التآكل و حساسية مادة فراش أنابيب الصرف الصحي لعملية التعرية. حيث تم تتبع الإزاحة الأرضية المقابلة من خلال مقارنة الصور الفوتوغرافية باستخدتم اداة قياس السرعة الجزيئية (PIV).

أشارت النتائج إلى أن حجم جسيمات التربة وعرض التسرب هما أكثر العوامل المؤثرة على تآكل التربة الناجم عن أنبوب الصرف الصحي المعيب من بين العوامل الأخرى. حيث تتناسب كمية التربة المتآكلة التي تم جمعها عكسيا مع نسبة حجم جسيمات التربة إلى حجم التسرب. أظهرت نتائج التجارب وتحليل البيانات أن التربة تستنزف خلال التسرب في الأنبوب بسهولة وباستمرار عندما تكون نسبة D70 / B أقل من 0.17. دراسة مادة تضمين الأنبوب

(الصنف (D) وفقاً للمواصفات العراقية) ، وبالمقارنة مع التربة الرملية المحلية ، أظهر الصنف (D) مقاومة أكبر للتآكل وبنسبة تتراوح بين (50-90%) حسب عرض التسرب ، حيث كانت التربة الرملية المحلية اكثرعرضة للتآكل بسبب تدفق المياه الدورية. جزيئات التربة ذات الحجم 0.42 ملم كانت اكثر عرضة للهروب من خلال التسرب . التربة التي تمتلك محتوى مائي ابتدائي 5% كانت تتاكل اكثر بنسبة 7% والتي تحتويعلى محتوى مائي ابتدائي 10% تتاكل اكثر ب 16%. يوفر نموذج التنبؤ التحليلي الأبعاد في الدراسة الحالية مقاربات فعالة "للتنبؤ بتآكل التربة" للتربة الرملية المحلية بسبب أنبوب الصرف الصحي المعيب.

جمهورية العراق
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# تقييم تأثير التسرب في انابيب المجاري على البنى التحتية

رسالـــــــــة

مقدمة إلى كلية الهندسة في جامعة كربلاء

وهي جزء من متطلبات نيل درجة ماجستير في هندسة البنى التحتية

من قبل :

علي ناصر غلام

(بكالوريوس علوم في الهندسة المدنية 2012)

بإشراف:

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