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공학석사 학위논문

Evaluation of Seepage Pressure through Damaged Sewerage Pipe Based on Numerical Analysis

수치해석을 기반으로 한 손상된 하수관에서의 침투압 평가

2016년 8월

서울대학교 대학원

건설환경공학부

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지도 교수 정 충 기

이 논문을 공학석사 학위논문으로 제출함
2016년 7월

서울대학교 대학원
건설환경공학부
박 재 찬

박재찬의 공학석사 학위논문을 인준함
2016년 7월

위 원 장 ______ 박 준 범 ______ **(인)**

부위원장 ______ 정 충 기 ______ **(인)**

위 원 ______ 조 완 제 ______ **(인)**

Abstract

Evaluation of Seepage Pressure through the Damaged Sewerage Pipe Based on Numerical Analysis

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Recently, interests for ground cave-ins has been growing due to its increasing occurrences and social damages. Ground cave-in is occurred mainly by the damaged sewerage pipe. Through the damaged part of the pipe, ground water and soil particles flow and loss of soil of ground happens. Continuous soil loss leads weaken ground capacity and finally to ground collapses. So it is very important to minimize soil loss, and how each factors applying to seepage pressure. In this study, burial depth, crack width, pipe diameter, rainfall intensity were considered to be influencing factors.

Finite element method (FEM) was applied to perform this study. MIDAS GTS NX was used to perform analysis. Conditions for analysis was basically based on conditions of Gangnam station, Seoul, Korea. Rainfall intensity was transformed to hydraulic head of inside the pipe.

Analysis procedure for seepage analysis at the damaged pipe was suggested. Performing analysis, determining the range of seepage analysis (Hydraulic gradient≥1), calculating average hydraulic gradient, seepage forces per unit volume, and determining seepage pressure at the damaged pipe is a sequence for analyzing.

For the analysis results, there are 4 main results. First, as damaged width increases, seepage force at region for calculating seepage force is increased and seepage pressure at damaged area is decreased. Second, as burial depth increases, seepage force and seepage pressure both decreased. Third, as diameter increases seepage pressure is decreased. But it affects very weakly to seepage pressure. Finally, as rainfall intensity increases, seepage pressure also increased.

Keywords: seepage, seepage pressure, damaged sewerage pipe, seepage analysis, ground cave-in

Student Number: 2014-21503

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Chapter 1 Introduction

1.1 Background

Recently, interests for ground cave-ins has been growing due to its increasing occurrences and social damages. Particularly, in 2015, urban ground cave-ins were broadcasted in news almost every day.

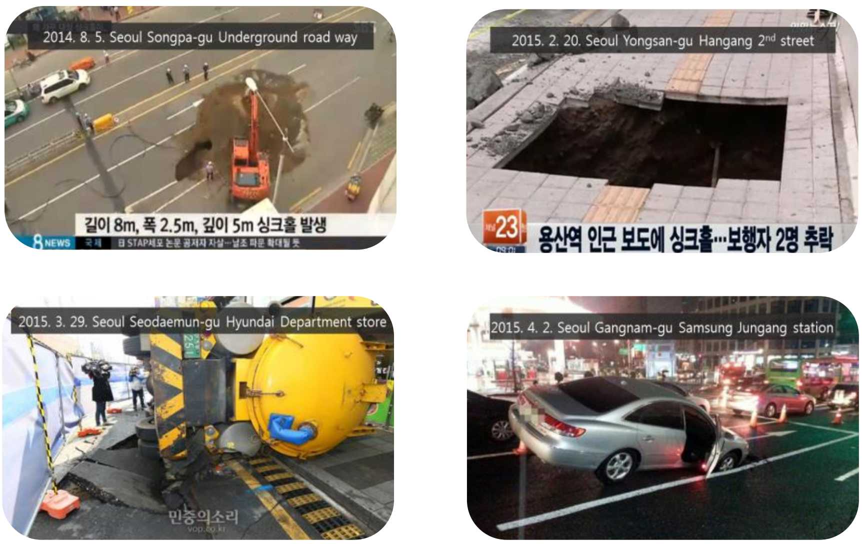

Figure 1.1 Increase of ground cave-in occurrences

'Sinkhole diagnosis and its measure' policy forum said ground cave-in occurrence is increasing from 2010 to 2013, with average annual increase over 20%. They warned if proper measure is not concerned, damage from ground disaster will grow.

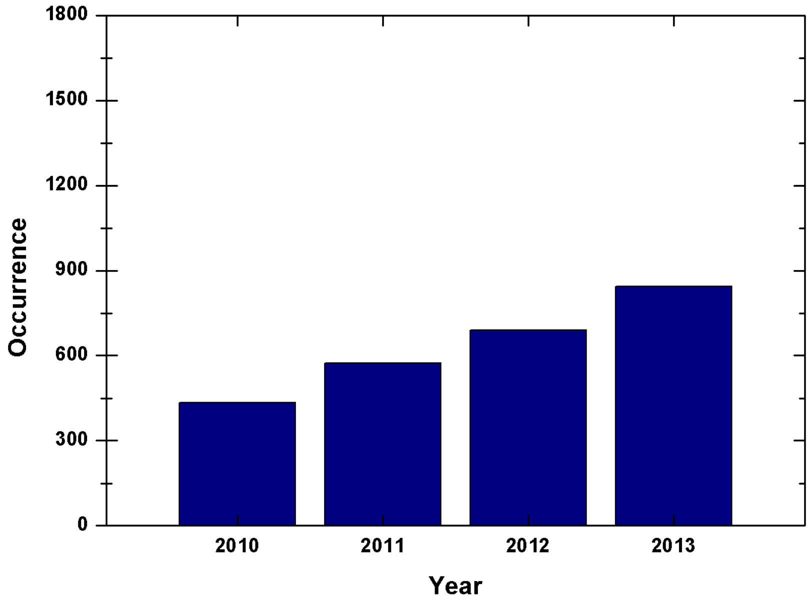

Figure 1.2 Annual occurrence of ground cave-ins in Seoul

Causes of unban ground cave-ins are divided as damaged sewerage pipes, excavations, and damaged water supply. Damaged sewerage pipe is a main cause of ground cave-ins occur. Age of sewerage pipes that are 20yrs over are 54.5% at 2010, and at 2013, it became 73.3%, and still growing.

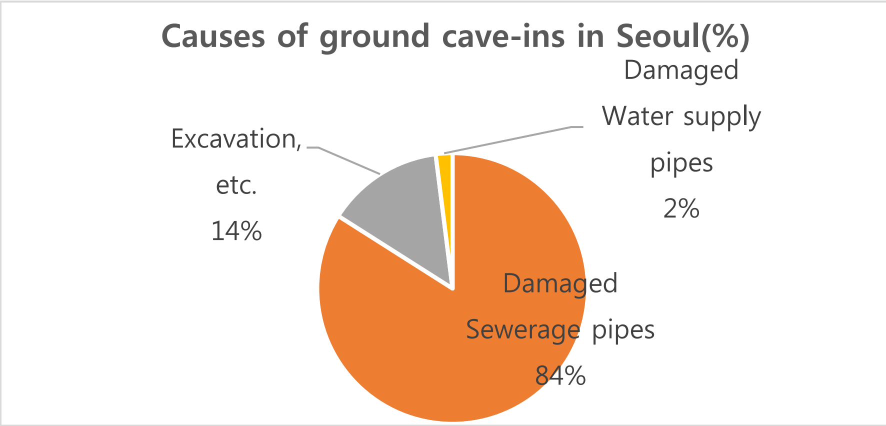

Figure 1.3 Causes of ground cave-ins in Seoul

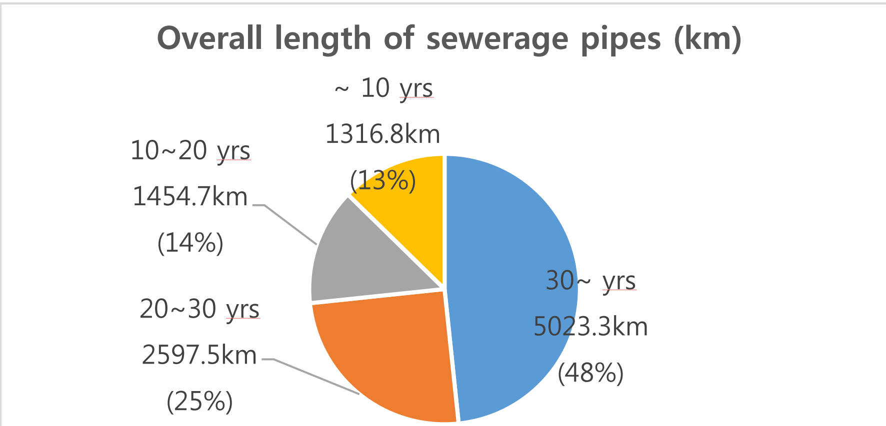

Figure 1.4 Overall length of sewerage pipes in Seoul

A process of ground cave-in occurrence is described as below picture and texts.

① Cracks at sewerage pipes developed

② Groundwater flow through crack of the pipe and soil loss occurs

③ Ground collapses as cavity expanded

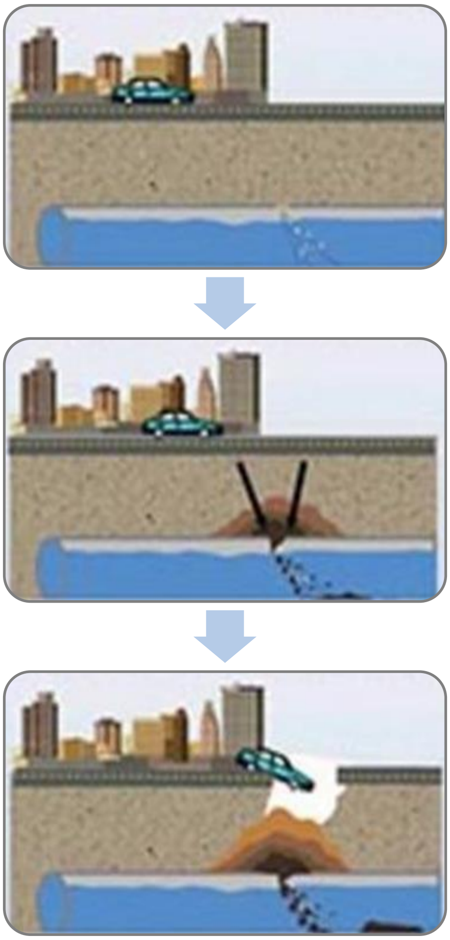

Figure 1.5 Process of ground cave-in occurrence

As described in the figure 1.5, soil loss is a main cause of ground cave-in, and soil loss is occurred due to groundwater flow near the damaged sewerage pipe.

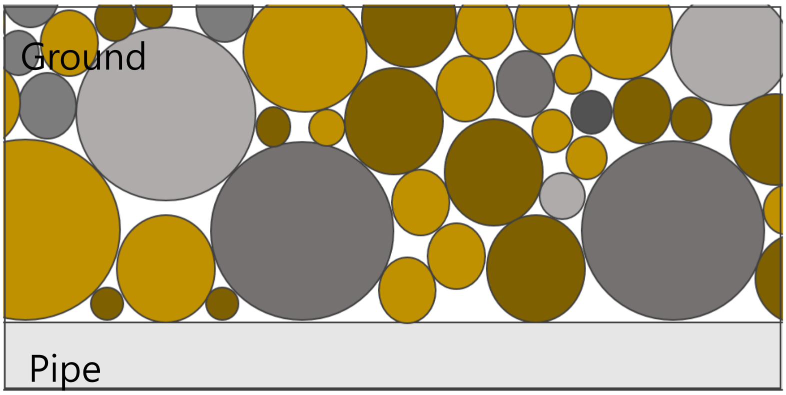

Figure 1.6 Pipe without crack

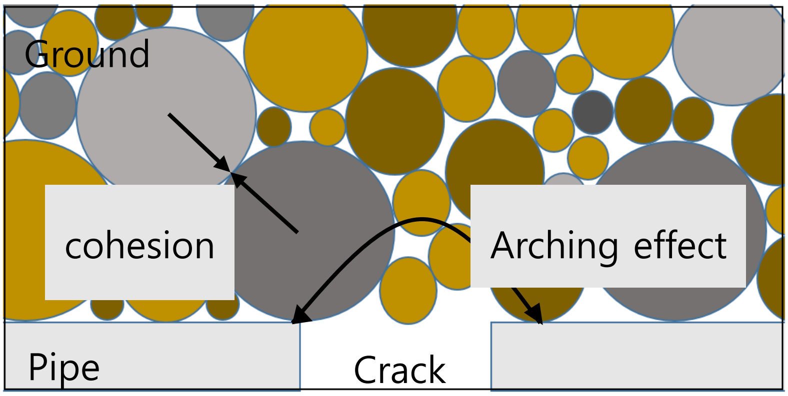

Figure 1.7 Pipe with crack

Soil loss is affected by driving force (seepage force and soil weight) and resisting force (cohesion force and arching effect). And it can be described as figure 1.6 and 1.7. Pipe without crack and pipe with crack are described. Before crack occurs, soil particles are under stable condition. As crack occurs, soil particles are forced to leak by their self-weight and resisted by cohesion force and arching effects. When rain comes, water flow outside through pipe crack and make water ground level higher. When rain stops, groundwater flow into the pipe and seepage force is affected to soil particle above the crack. Driving force which was only consisted of self-weight is now consists seepage force. To minimize soil loss, it is important to minimize driving force and maximize resisting force.

1.2 Objectives & Scope of This Study

This dissertation deals with the seepage force at damaged parts of the cracked pipe based on numerical analysis. By simulating underground and rainfall condition of Gangnam station, Seoul, 2D seepage analysis was performed.

The specific objectives of this study are as follows:

1. Suggesting a method of evaluating seepage force (pressure) at damaged pipe
2. Evaluating a seepage force (pressure) at damaged pipe
3. Analyzing influencing factors for seepage forces and vulnerable conditions

To find out the effect of influencing factors, some factors were considered. Burial depth of pipe, diameter of pipe, crack size at damaged pipe, and rainfall intensity were considered as factors that affect seepage pressure.

In this study, a method of evaluating seepage force (pressure) at damaged pipe is suggested.

1.3 Dissertation Organization

This dissertation documents evaluate seepage force at damaged sewerage pipe.

Chapter 1.Introduction

Introduction includes research background and objectives, and dissertation organization was described.

Chapter 2.Literature Review

Literature review for definitions of seepage and seepage force, influencing factors for seepage pressure, method of analyzing seepage pressure are described.

Chapter 3.Seepage analysis

The conditions for analysis, analyzing procedure, and results and discussions are described.

Chapter 4.Conclusions and Recommendations

Based on analysis results, experimental results soil thrust-slip displacement curve fitted with theoretical model. And the coefficient of earth pressure K_S is provided for evaluate the side thrust

Chapter 2 Literature Review

2.1 Seepage

2.1.1 Definitions of seepage and seepage force (pressure)

Seepage and Seepage force (pressure) should be defined at first. Seepage is a phenomenon that groundwater flow due to the difference of total head in ground. It can be explained by a picture below.

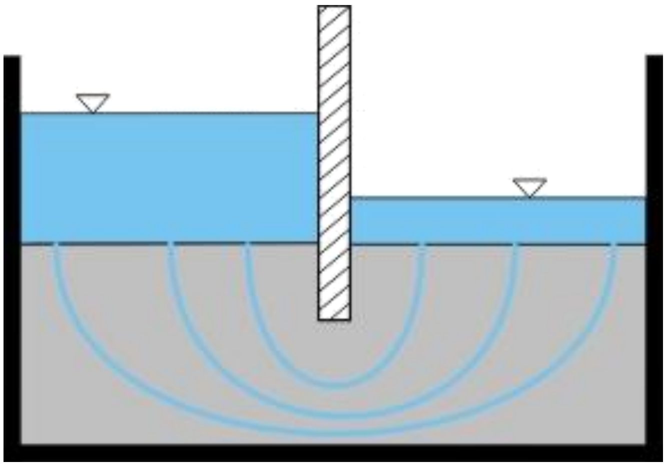

Figure 2.1 Seepage phenomenon

Darcy said seepage flow can be expressed as

$$v = ki$$

$$i = \frac{\Delta H}{L}$$

as v=flow velocity in soil, k=permeability coefficient, i=hydraulic gradient, ΔH = total head diffeence, L= length of flow line. (Lambe & Whitman, 1979)

Due to this phenomenon, a drag force that is affected to soil particle occurs. It is called seepage force. It is defined as drag force applied to soil skeleton due to the moving water. As shown in Figure 2.2, water flows through soil particles. During this process, water flows with friction which is a cause of seepage force. Seepage force per unit volume can be expressed as a formula below. (Lambe & Whitman, 1979)

$$\frac{Seepage\ Force}{Unit\ Volume} = \frac{hA\gamma_w}{LA} = \mathrm{i}\gamma_w$$

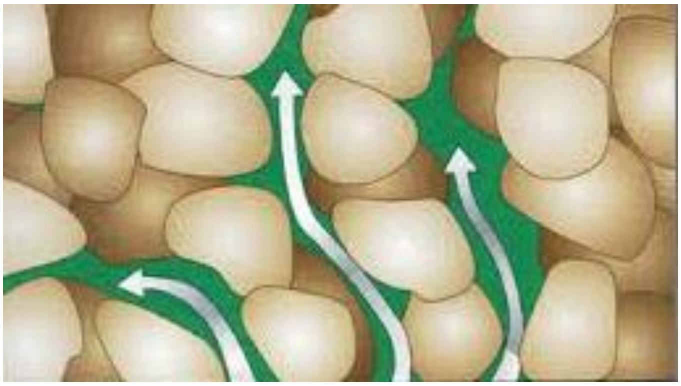

Figure 2.2 Seepage phenomenon (2)

2.1.2 Influencing factors for seepage force

There are no research about seepage forces at damaged sewerage pipe yet. But there are some studies about seepage force at crown of tunnels or tunnel faces. Situations for tunnels are quite similar to sewerage pipe due to its underground locations and affected by seepage forces.

Influencing factors for seepage forces are known as ground water level and depth of tunnel. (Lee et al (2006), Shin et al (2007), Lee et al (2003)) Lee et al (2006) and Shin et al (2003) performed numerical analysis by simulating ground conditions shown below. They tried to see how 2 factors affected to seepage forces.

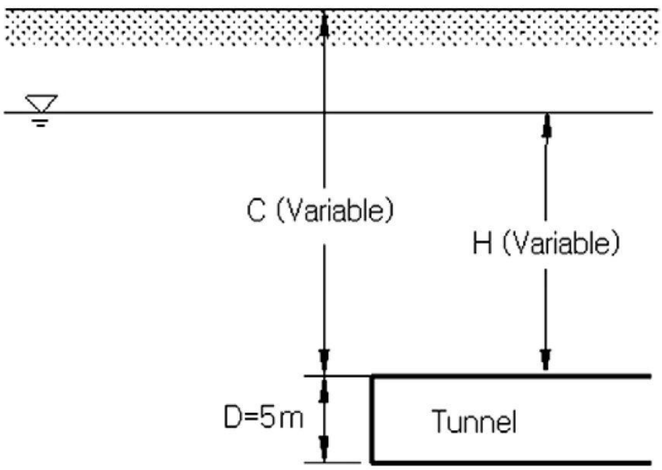

Figure 2.3 Ground conditions (Lee et al (2006), Shin et al (2007)

As the brief results, higher ground water level results in higher seepage pressure (Lee et al (2006), Shin et al (2007), and deeper the tunnel location results in less seepage pressure. (Shin et al (2007)). But Lee et al (2006) did not think tunnel depth and seepage force has no relation.

Table 2.1 Seepage pressure results (Lee et al (2006))

	C/D=2	C/D=3	C/D=4
H/D=1.5	29.82 kPa	29.82 kPa	29.82 kPa
H/D=2.0	46.50 kPa	46.50 kPa	46.50 kPa
H/D=2.5	99.08 kPa	64.26 kPa	64.26 kPa
H/D=3.0	147.15 kPa	70.83 kPa	70.83 kPa
H/D=3.5	171.68 kPa	109.68 kPa	90.35 kPa
H/D=4.0	196.20 kPa	151.27 kPa	98.20 kPa

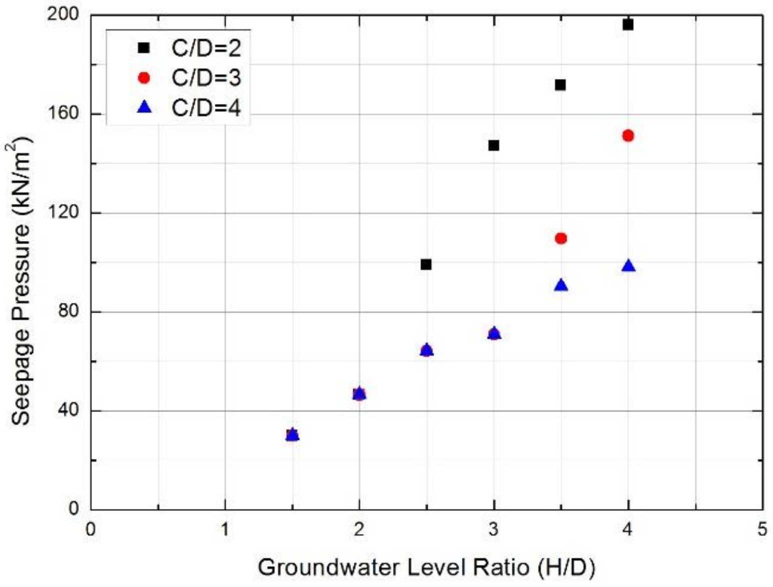

Figure 2.4 Seepage analysis results (Lee et al (2006))

Table 2.2 Seepage pressure results (Shin et al (2007))

	C/D=2.5	**C/D=5.0**	**C/D=7.5**	**C/D=10**
H/D=2.5	117.6 kPa	105.8 kPa	105.8 kPa	107.8 kPa
H/D=5.0	235.2 kPa	235.2 kPa	224.4 kPa	225.4 kPa
H/D=7.5	352.8 kPa	352.8 kPa	351.8 kPa	339.1 kPa
H/D=10	477.3 kPa	473.3 kPa	468.4 kPa	469.4 kPa

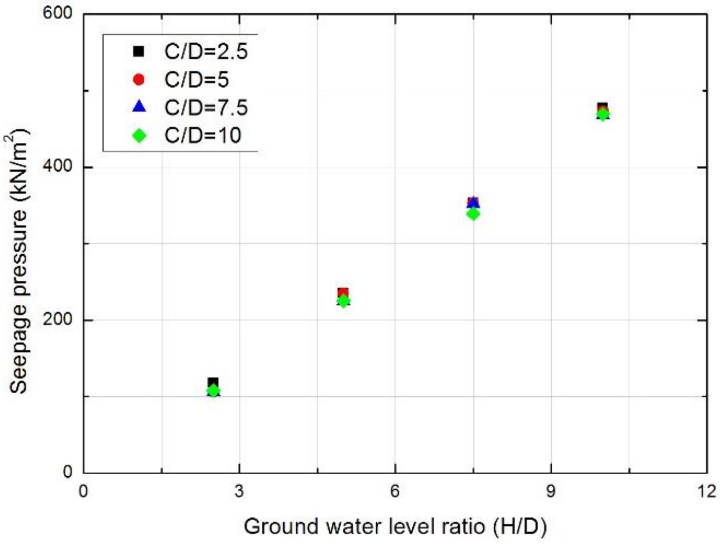

Figure 2.5 Seepage analysis results (Shin et al (2007))

2.2 Analysis method

2.2.1 Seepage analysis for tunnel seepage pressure

As explained above, seepage force studies at damaged sewerage pipes has not been performed yet. There is a study that explained how seepage force affect to a tunnel face. Lee et al (2003) explained collapse mechanism of a tunnel face which how tunnel face could collapse.

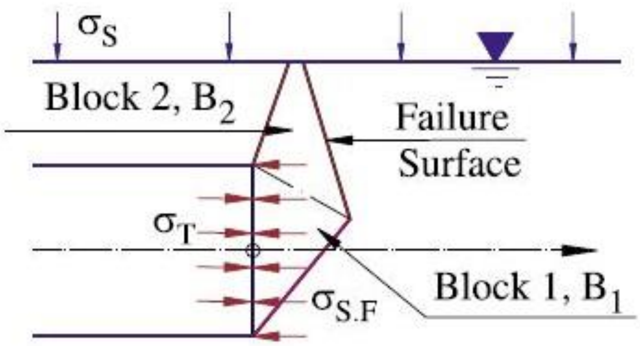

Figure 2.6 Collapse mechanism of a tunnel face

As shown at above figure 2.6, there are 2 conical blocks in front of tunnel face. There is specific method to calculate the failure surface, but it is not necessary to in this study.

By using tunnel collapse failure mechanism, Lee tried to calculate seepage force that affect to tunnel face. He used analysis program (pentagon 3D) to simulate underground condition. Tunnel, tunnel depth, sand, surcharge, water level were considered factors.

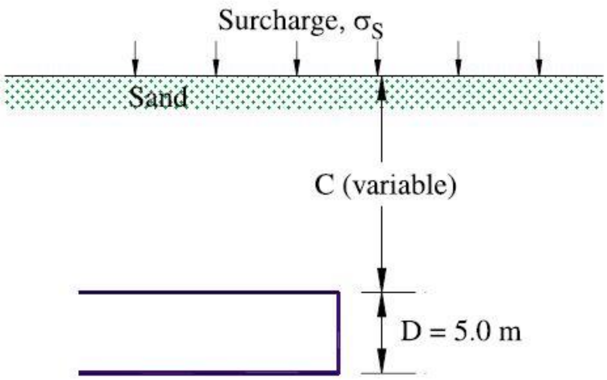

Figure 2.7 Ground conditions for analysis (Lee et al (2003))

The analyzing ends with its total head distribution. After analyzing, he calculated seepage force by using total head differences. Total head distribution can be used to solve hydraulic gradient. As mentioned above, seepage force per unit volume can be expressed as $i\gamma_w$. And by using expected failure surface, volume of 2 conical blocks could be calculated. Finally, he could calculate seepage force and seepage pressure.

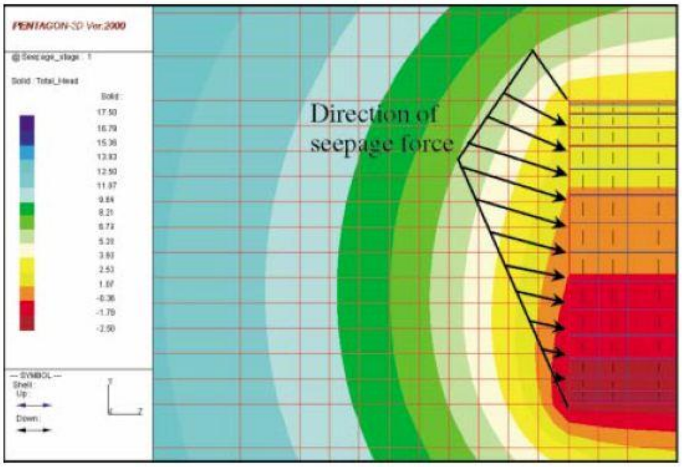

Figure 2.8 Total head distribution (Lee et al (2003))

But for the damaged sewerage pipe, there is no failure surface. To decide failure surface for the damaged sewerage pipe, a study for calculating seepage force at tunnel crown was also used. Lee et al (2006) tried to calculate how seepage force affect to tunnel crown. He performed numerical analysis by simulating underground condition shown as below figure 2.9.

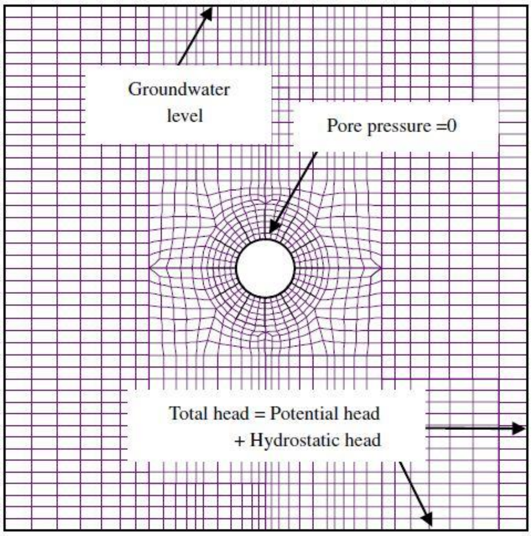

Figure 2.9 Boundary conditions for analysis (Lee et al (2006))

He considered tunnel crown and groundwater level. Pore pressure of 0 was applied to simulate drainage at tunnel crown.

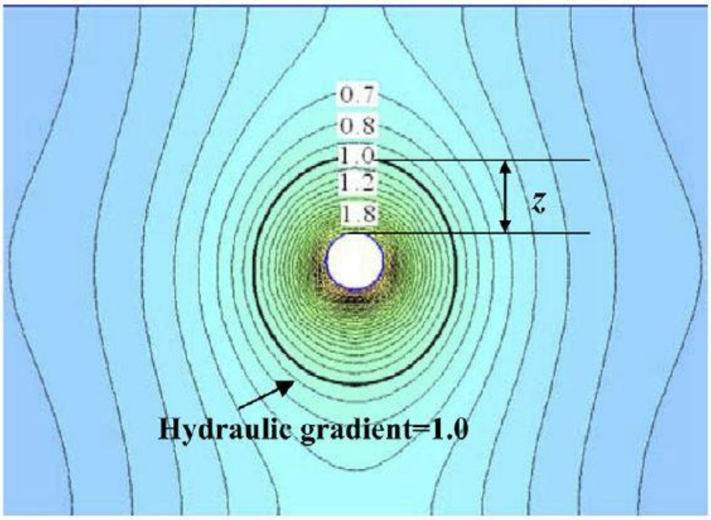

Figure 2.10 Hydraulic gradient distribution (Lee et al (2006))

Then he decided to use region for calculating the seepage force as specific region which has hydraulic gradient bigger than 1. A reason for this specific region was from a Darcy's law.

$$\mathrm{v} = \mathrm{ki}$$

From the Darcy's law, a velocity and a hydraulic conductivity has linear relationship. Lee et al (2006) said that when hydraulic gradient is higher than 1.0, the velocity becomes higher than the hydraulic conductivity so groundwater flows against the resistant force due to the soil mass with a large reduction of hydraulic head. The accumulated resistant force is transferred as effective stress and it affects to the tunnel crown.

After deciding the region, Lee calculated a seepage force by using a equation which was made by Atkinson and Mair (1983).

$$\frac{d\sigma_i'}{dS} = \gamma_w \mathrm{i}$$

$$\sigma_i' = \gamma_w \int i_r \, \mathrm{dr}$$

As, σ_i' is seepage force per unit volume, i is hydraulic gradient, S is distant from a crown.

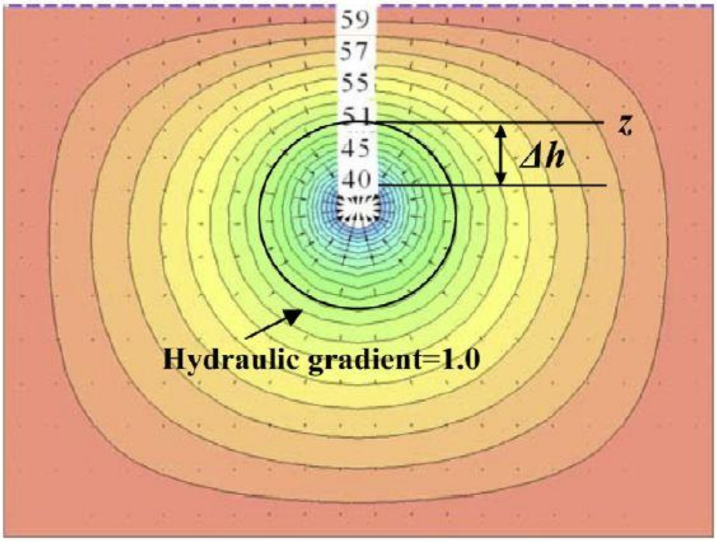

Figure 2.11 Total head distribution (Lee et al (2006))

By applying above equations, Lee et al (2006) could calculate seepage pressures.

Chapter 3 Seepage analysis

3.1 Conditions for analysis

3.1.1 Analysis software

A study of seepage force at damaged sewerage pipes was performed. A basic analysis was performed for finite element method (FEM). To perform this study, MIDAS GTS NX software was used. To analyze exact seepage pressure, it should be 3 dimensional analysis, but in this study, 2 dimensional analysis was performed only to find out influencing factors.

It has various module which can be used for various conditions. In this study, seepage module was used.

3.1.2 Simulating condition

In this study, a specific condition was simulated. It can be explained by a series of figures 3.1.

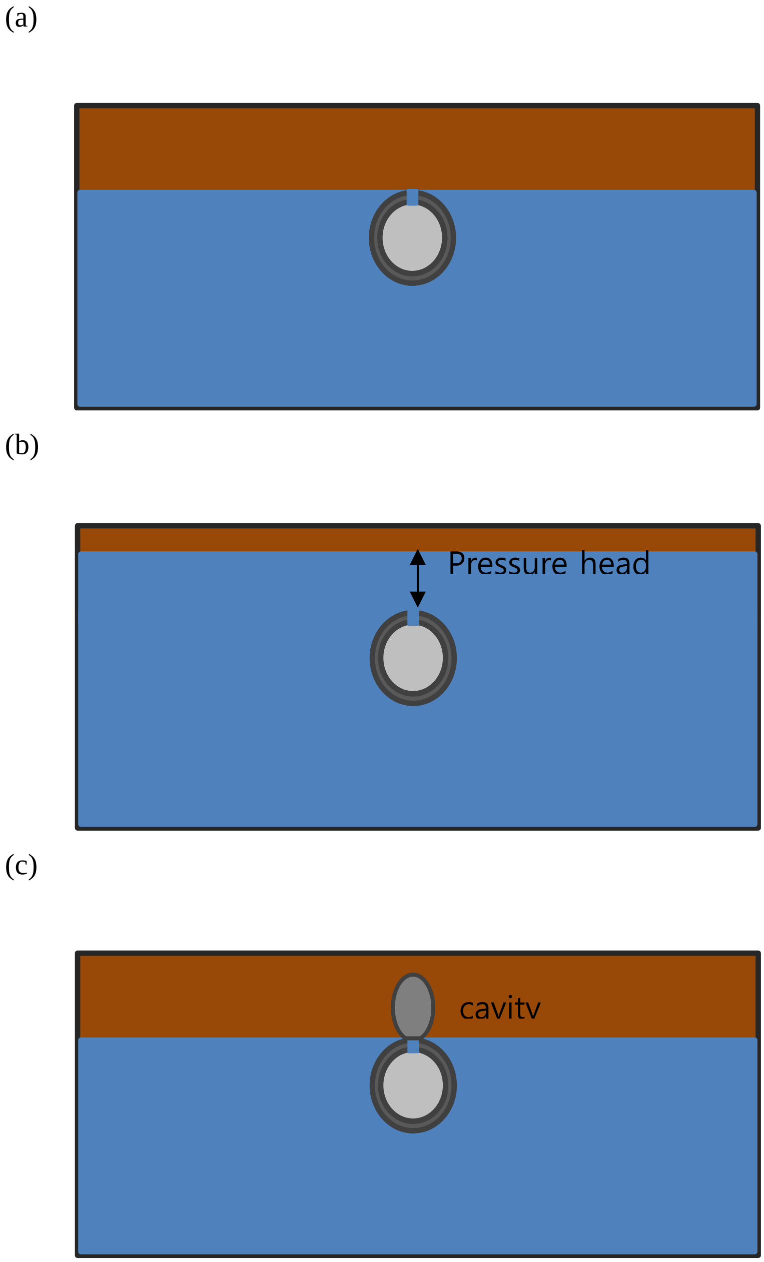

Figure 3.1 Ground water level change

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From (a) to (c), figures explain initial stage, rainfall stage, and rain stop stage. Conditions that this study simulates is figure (c), after the groundwater flow in to the pipe. Figure (c) also contains cavity formation. Maximum seepage pressure occurs at the moment the groundwater flow in to the pipe.

3.1.3 Modelling ground

Modelling ground simulated the underground condition of Gangnam station, Seoul, Korea. Modelling ground size was decided 20m width and 5m depth. Due to the pipes' relative locations at Gangnam station. They were 20m apart. For the depth of 5m, it was considered to be an enough depth that groundwater flow does not affects to seepage pressure. Permeability coefficient was selected to 0.0001cm/sec from permeability tests of Mt. Gwan-ak weathered soil. Burial depths were considered to be 0.5, 1, 1.5m. From sewerage pipe standard specification (Ministry of environment, 2010), sewerage pipe should be buried deeper than 1m. So to find out the effect of burial depth, 0.5m and 1.5m depths were added.

3.1.4 Modelling sewerage pipes

Pipe diameter was considered to be 1000mm for a basic condition. And to find out the effect of pipe diameter, 700mm, 500mm and 300mm diameter were also considered. 1000mm of diameter is a most popular diameter at Gangnam station.

For damaged width of diameter, there are no documents or studies performed for damaged sewerage pipes. 5, 10, 15, 20cm was applied to see the effect of damaged area.

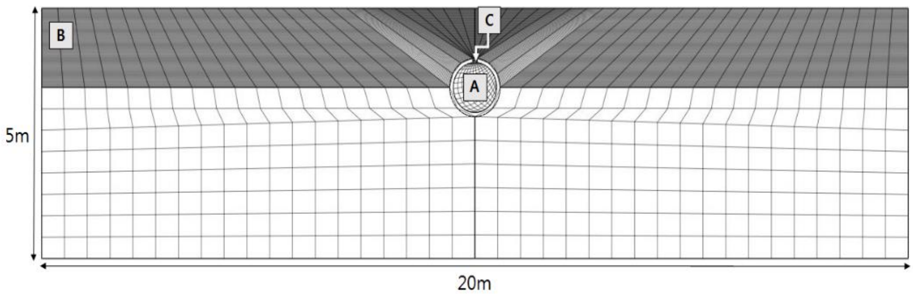

Figure 3.2 Mesh for analysis

Above figure is the mesh for analysis. Ground condition and pipe condition are considered. Pipe (A), ground (B), damaged part of the pipe (C) are considered.

3.1.5 Rainfall intensity

Rain is a main cause of occurrences of ground cave-ins. To see how rainfall intensity affects to seepage pressure, 50, 40, 30, 20mm/hr of rainfall intensities were considered. In the software, MIDAS GTS NX, it needs inner pipe hydraulic head, not a rainfall intensity. To make a relationship with rainfall intensities and hydraulic pressure, a study from National Disaster Management Institute was loaded. They tried to perform an experiment about hydrodynamic force to lifting up Manhole cover. They simulated the condition of Gangnam station sewerage system.

Table 3.1 Relationship between rainfall intensity and pressure head

Rainfall intensity (mm/hr)	20	30	40	50
Flow rate(m^3/s)	0.45	0.87	1.30	1.68
Pressure head of inner pipe (cm)	33.3	40.0	46.7	70.0

Flow rates are calculated under the condition of Gangnam station.

3.1.6 Boundary condition

Boundary conditions for this study was Flow rates are calculated under the condition of Gangnam station.

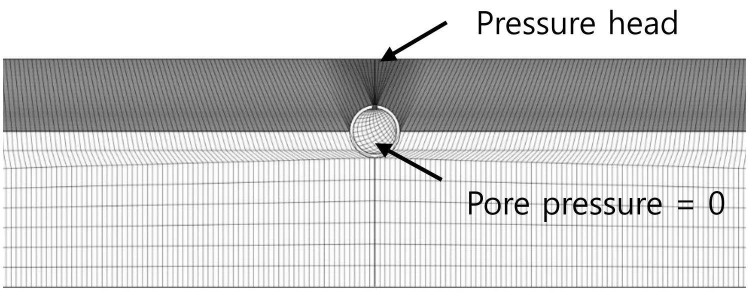

Figure 3.3 Boundary condition for analysis

To simulate a condition that we want, pressure head which we found was applied to ground, and 0 pore pressure applied to inside of pipe to simulate drainage.

3.2 Analysis procedure

By using given conditions above, numerical analysis was performed. After using program, there were specific procedure to calculate seepage forces.

1. •Perform a finite element analysis under a determined condition
2. •Determine the range of seepage analysis (Hydraulic gradient ≥ 1)
3. •Calculate average hydraulic gradient inside the analysis range
4. •Calculate seepage forces per unit volume using average hydraulic gradient
5. •Measure the volume of analysis range
6. •Estimate seepage force by multiplying seepage force (4) and volume (5)
7. •Determine seepage pressure by dividing seepage force (6) over damaged area of pipe
8. •Repeat 1~7 for various conditions

Figure 3.4 Analysis procedures

From first step to explain, performing numerical analysis is the first step. By using given conditions, MIDAS GTS NX software was used. Total head distribution or flow line distribution can be obtained.

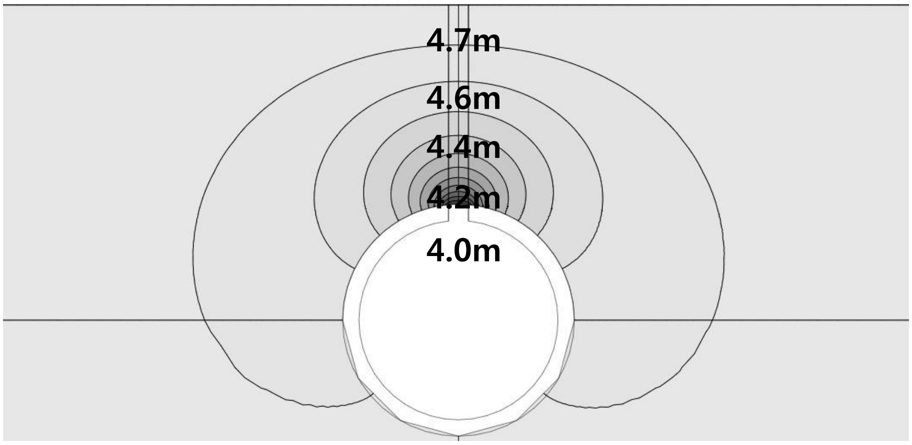

Figure 3.5 Total head distribution

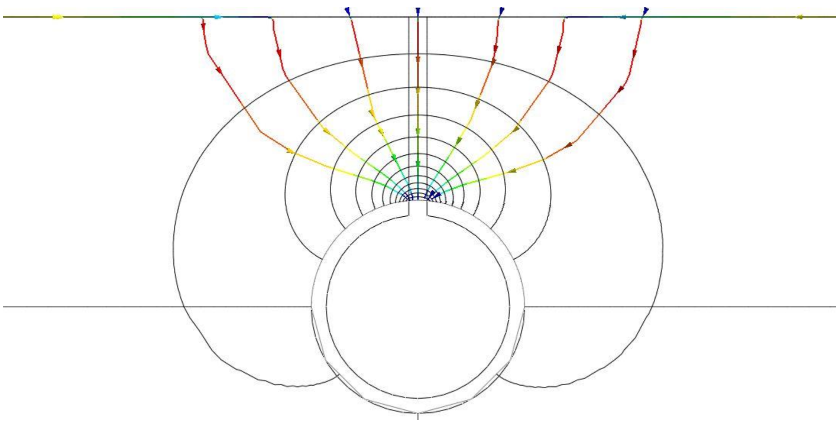

Figure 3.6 Flow line distribution

Next step is to determine range of calculating seepage pressure. As mentioned before, region for calculating seepage pressure is determined by the hydraulic gradient criteria.

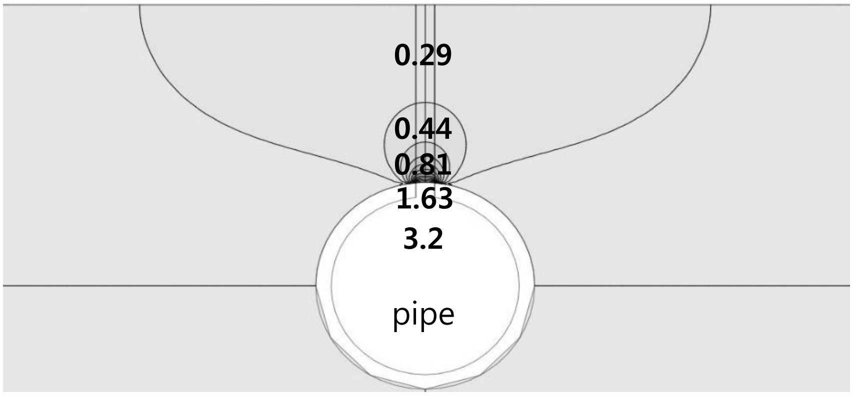

Figure 3.7 Hydraulic gradient distribution

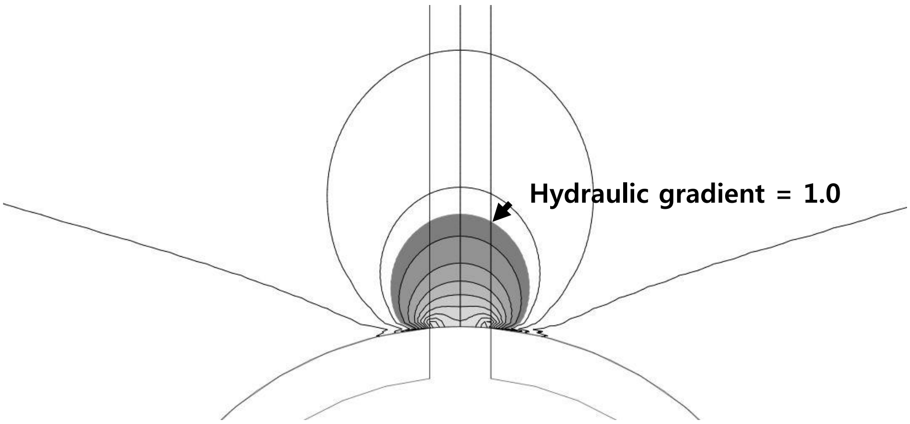

Figure 3.8 Hydraulic gradient distribution (Hydraulic gradient≥1)

For proper analysis, we could draw a range that has higher hydraulic gradient than 1.0. Figure 3.8 shows that.

After determining the range of seepage analysis, we need to average the hydraulic gradients. By using 'Extract results', we could get an average value of hydraulic gradient.

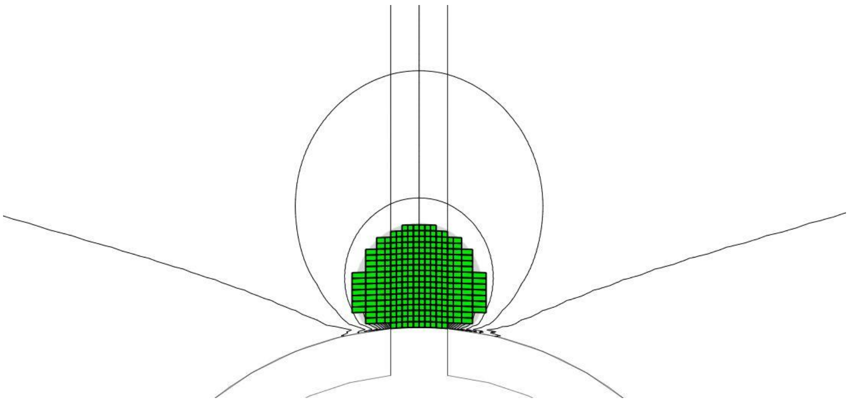

Figure 3.9 Selecting elements to get average hydraulic gradient

By using the results of average hydraulic gradient, we can get a seepage force per unit volume.

$$\mathrm{i}\gamma_w = i \times \frac{1t}{m^3} = i \times \frac{1000kg}{m^3}$$

$$= i \times \frac{1000kg}{m^3} \times \frac{9.8m}{sec^2}$$

$$= 9.8 \times i\ kN/m^3$$

Next step is to measure the volume of analysis range. A software 'image J' was used to measure the range of calculating area. After measuring the volume of analysis range and calculating seepage forces, multiplying seepage force per unit volume and volume of analysis range is needed to estimate seepage forces. To get seepage pressure, seepage forces should be divided by damaged area of the sewerage pipe.

After all of those procedure, to get every conditions of seepage pressure, repeating those procedure for every condition is needed.

3.3 Results and discussions

3.3.1 Burial depth & damaged area

After finishing analyzing, we could get results. Firstly, the most influencing factors, burial depth and damaged area were discussed. For the rainfall intensity of 50mm/hr (hydraulic head: 70cm), analysis was performed.

Table 3.2 Calculating procedure (Burial depth: 0.5m) – damaged area

Damaged area (cm)	Average hydraulic gradient	Seepage force/Unit volume (kN/m^3)	Area of region for calculating (m^3)	Seepage force (kN)	Seepage pressure (kPa)
5	2.4	23.5	0.029	0.68	13.51
10	2.1	21.0	0.049	1.03	10.27
15	2	19.6	0.068	1.33	8.90
20	1.9	18.3	0.087	1.59	7.96

Table 3.3 Calculating procedure (Burial depth: 1.0m) – damaged area

Damaged area (cm)	Average hydraulic gradient	Seepage force/Unit volume (kN/m^3)	Area of region for calculating (m^3)	Seepage force (kN)	Seepage pressure (kPa)
5	2.28	22.3	0.015	0.33	6.51
10	2.03	19.9	0.027	0.53	5.33
15	1.87	18.3	0.038	0.70	4.70
20	1.8	17.6	0.048	0.85	4.23

Table 3.4 Calculating procedure (Burial depth: 1.5m) – damaged area

Damaged area (cm)	Average hydraulic gradient	Seepage force/Unit volume (kN/m^3)	Area of region for calculating (m^3)	Seepage force (kN)	Seepage pressure (kPa)
5	2.24	22.0	0.011	0.24	4.78
10	1.94	19.0	0.020	0.39	3.88
15	1.85	18.1	0.030	0.55	3.65
20	1.72	16.9	0.035	0.60	2.98

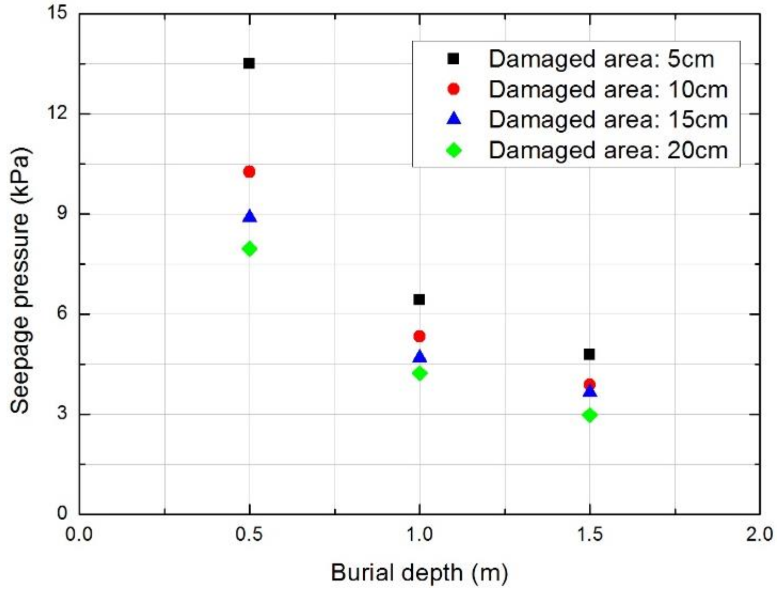

Figure 3.10 Seepage pressure-burial depth

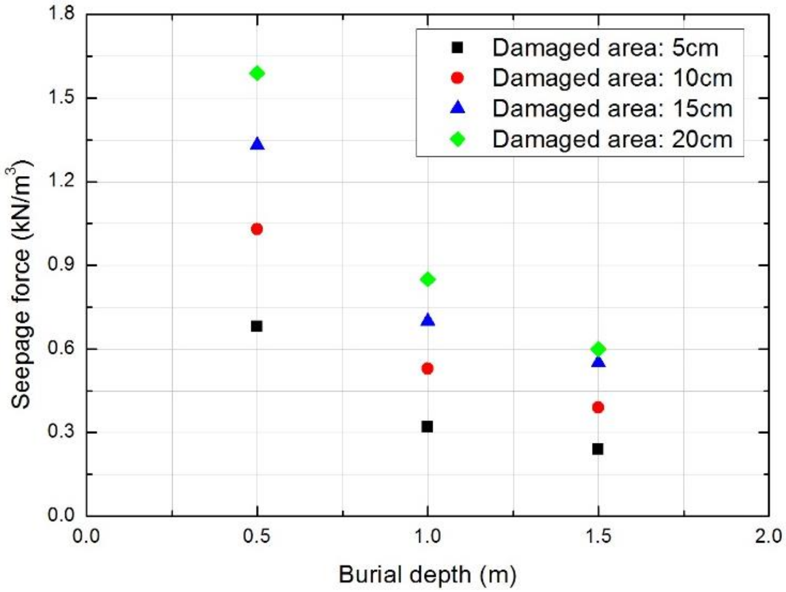

Figure 3.11 Seepage force-burial depth

To summarize the results, firstly, as damaged area increases, seepage force increases. But in seepage pressure, it decreases, because damaged area that was a dividing factor were increased. So, damaged area was dominant.

Secondly, as burial depth increases, seepage force and seepage pressure are decreased. It was same results as Shin et al (2007).

As mentioned before, sewerage pipe standard specification says burial depth for sewerage pipe needs to be deeper than 1.0m. By the results of this analysis, keeping burial depth specification seems to be very important.

3.3.2 Diameter

There are various kinds of pipe diameter under the ground. So there is a need to analyze diameter effects.

Table 3.5 Calculating procedure - diameter

Diameter (mm)	Average hydraulic gradient	Seepage force/Unit volume (kN/m^3)	Area of region for calculating (m^3)	Seepage force (kN)	Seepage pressure (kPa)
300	2.67	26.2	0.012	0.33	6.54
500	2.58	25.3	0.013	0.32	6.48
700	2.5	24.5	0.013	0.32	6.45
1000	2.28	22.3.	0.014	0.32	6.43

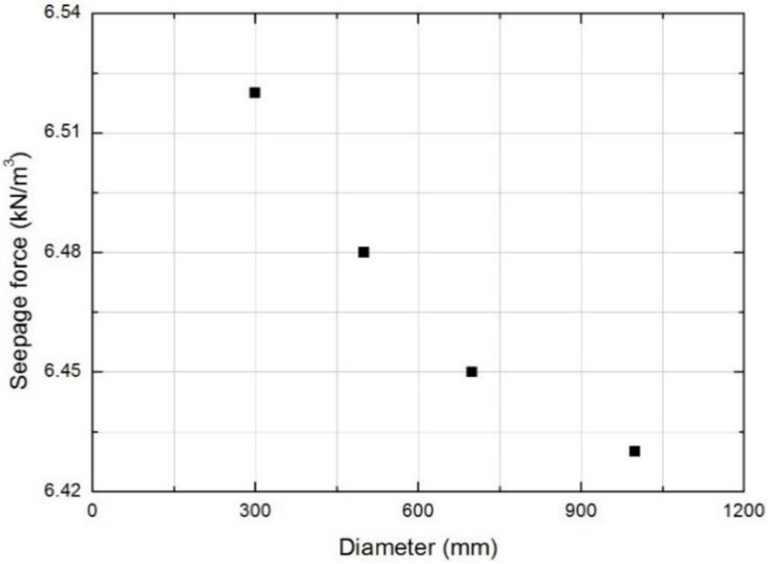

Figure 3.12 Seepage pressure-diameter

To summarize the results, firstly, as diameter increases, area of region increases and average hydraulic gradient decreases. As the results, seepage pressures decreases.

But the biggest seepage pressure was 6.52 kPa and the smallest one was 6.43 kPa. So it says diameter is not a very strongly effective factor.

3.3.3 Rainfall intensity

Rainfall intensity is very important factor that affects seepage pressure. It has an impact to ground water level changes. For the damaged area of 10cm, burial depth and rainfall intensity were changed.

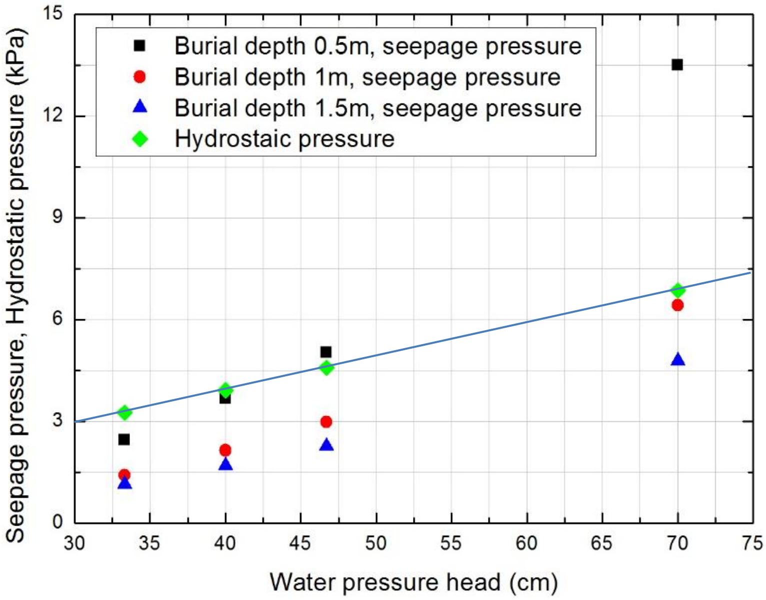

Figure 3.13 Seepage pressure-water pressure head

Fairly, as rainfall intensity (hydraulic head) increases, seepage pressure also increased. Striking results was happened at a condition that water pressure head 70cm and burial depth of 0.5m. The seepage pressure was increased rapidly. It is because hydraulic head of 70cm is bigger than burial depth 0.5m. It seems that the difference of 2 values made that results.

Chapter 4 Conclusions

Nowadays, urban ground cave-ins are magnified as serious ground disaster. Ground cave-in is occurred mainly by the damaged sewerage pipe. Through the damaged part of the pipe, ground water and soil particles flow and loss of soil of ground happens. Continuous soil loss leads weaken ground capacity and finally to ground collapses. So it is very important how each factors applying to seepage pressure. In this study, burial depth, crack width, pipe diameter, rainfall intensity were considered to be influencing factors.

Finite element method (FEM) was applied to perform this study. MIDAS GTS NX was used to perform analysis. Conditions for analysis was basically based on conditions of Gangnam station, Seoul, Korea. Rainfall intensity is transformed to hydraulic head of inside the pipe.

Analysis procedure for seepage analysis at the damaged pipe was suggested. Performing analysis, determining the range of seepage analysis (Hydraulic gradient≥1), calculating average hydraulic gradient, seepage forces per unit volume, and determining seepage pressure at the damaged pipe is a sequence for analyzing.

For the analysis results, there are 4 main results. First, as damaged width increases, seepage force at region for calculating seepage force is increased and seepage pressure at damaged area is decreased. Second, as burial depth increases, seepage force and seepage pressure both decreased. Third, as diameter increases seepage pressure is decreased. But it affects very weakly to seepage pressure. Finally, as rainfall intensity increases, seepage pressure also increased.

By the analysis results, vulnerable conditions for urban ground cave-ins were figured out. Also, following the standard specification is very important to reduce seepage pressure at the damaged sewerage pipe.

Additional studies are recommended for this study. First of all, 3 dimensional seepage analysis is strongly recommended. It needs to simulate the shape of damaged area exactly. Also the underground condition for real ground cave-in occurred place is necessary. The analysis needs to be practical, not only scholar study.

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초 록

최근 도심지에서 발생하는 지반함몰과 그로 인한 사회적 피해가 증가하였지만 관련 연구가 충분히 수행되지 않아 연구의 필요성이 부각되고 있다. 도심지에서 발생하는 지반 함몰은 하수관 손상으로 인한 경우가 대다수이며, 하수관의 손상은 노후화로 인한 파손 비율이 크다. 하수관 손상부를 통한 지하수 유입, 유출 과정에서 지반의 흙 입자들이 하수관 내부로 유실되고, 이 과정에서 생성된 공동으로 인해 지반함몰이 발생한다.

본 연구는 지하수 유출 과정에서 하수관 손상부에 가해지는 침투압이 토사 유출에 영향을 준다고 판단하여, 유한요소 해석 프로그램 (MIDAS GTS NX)을 사용하여 서울 강남역 지반 및 하수관거 조건을 모사하여 하수관 주변에서의 침투 해석을 수행하였다. 하수관 매설 깊이, 하수관 손상부 폭, 하수관 관경, 강우 강도 조건을 변화시켜가며 그에 따른 침투압 결과를 분석하였다.

본 연구에서는 기존에 규명되지 않은 하수관 손상부에서의 침투압 산정 방법을 제안하였으며, 침투압의 영향 인자들을 분석하였다.

침투 해석을 통해 4가지 영향 인자들에 대한 결과를 얻을 수 있었다. 우선 손상부 폭이 커질수록 침투력 산정 범위 내부의 침투력은 커지지만 손상부에 가해지는 침투압은 작아지는 경향을 확인할 수 있었다. 하수관 매설 깊이의 경우, 깊이가 깊을수록 침투력과 침투압 모두 감소하였다. 하수관의 직경은 커질수록 침투압이 작아짐을 확인하였으나, 이는 미미한 영향 만을 주었다.

강우 강도는 클수록 하수관 내부 압력 수두가 커져 침투압도 커짐을 확인 할 수 있었다.

주요어: 침투, 침투압, 손상 하수관, 침투 해석, 지반 함몰

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