

Evaluation of sewer network resilience index under the perspective of ground collapse prevention

Chuanli Zhang , Jeill Oh and Kyoohong Park*

Department of Civil Engineering, Chung-Ang University, 84 Heukseok-ro, Dongjak-gu, Seoul 06974, Korea

*Corresponding author. E-mail: kpark@cau.ac.kr

 CZ, 0000-0001-6652-0883

ABSTRACT

Generally, when evaluating the resilience of infrastructure, the four properties of resilience (robustness, rapidity, resources, and redundancy, 4Rs) are widely considered. However, there is little research on the resilience assessment of sewer networks. Therefore, to establish a framework to evaluate sewer network resilience under the perspective of urban ground collapse prevention, this study considers the 13 second-level detailed indicators corresponding to the four first-level indicators (4Rs) based on literature reviews and experts' opinions. An analytic hierarchy process (AHP) is used to obtain relative weights of each indicator and a weighted sum method (WSM) is used to evaluate the sewer network resilience index (SRI). The evaluation system is applied to eight small blocks of selected drainage areas in Seoul, South Korea, and the SRI of eight small blocks are computed. This study could help the sewer management department to make decisions and manage sewer network assets that enhance the resilience of the sewer networks.

Key words: analytic hierarchy process, ground collapse, resilience index, sewer networks

HIGHLIGHTS

- The factors that affect the resilience of the sewer network under the perspective of urban ground collapse were identified and evaluated.
- AHP was used to evaluate the weights of the sewer network resilience indices.
- The quantitative value of the sewer network resilience was calculated via weighted sum method.

INTRODUCTION

The rapid development of urbanization, increasingly prominent climate change, and rapid economic development have brought serious environmental problems. The inevitable aging of urban infrastructure has caused many threats to cities, among which road collapse caused by infrastructure has attracted worldwide attention (Guarino & Nisio 2012). Many infrastructures, such as water and sewage pipes, gas pipes, and subways, buried under roads, are rapidly aging. In the future, the infrastructure used beyond legal service life will increase. Therefore, the risk of road collapses is also increasing. Inappropriate construction or maintenance of underground pipelines may also cause sudden damage to the road surface, i.e. subsidence, bulging, or collapse (Kuliczowska 2016a). As an important part of urban infrastructure, sewage pipes are a key element of most urban sanitation systems. According to previous reports and observations, joint separation, leakage, fracture, and collapse of pipes are the most common faults in sewage pipelines (WEF 2009). Sewer pipes are generally larger than other utility pipes and are installed deeper underground (Kuliczowska 2016b). Ground collapse accidents caused by damaged sewer pipes are usually more serious. As a metropolis in South Korea, Seoul often has related reports of ground collapse, of which a relatively large proportion is caused by damaged sewer pipes (Kwak *et al.* 2019). This paper focuses on the angle of dealing with road collapses caused by sewer pipe defects.

As shown in Figure 1, sewer pipes may be damaged in different ways over time. Small cracks or fractures can occur in old pipes, or misalignments can occur at a connection point. These openings may be tiny but still allow small amounts of dirt to sift into the pipe. That dirt is carried away with the wastewater, but over time, enough soil from above the pipe is flushed away that a hollow space can form above the pipe and below the street surface. If enough soil quietly sifts into the sewer, and a big enough

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (<http://creativecommons.org/licenses/by/4.0/>).

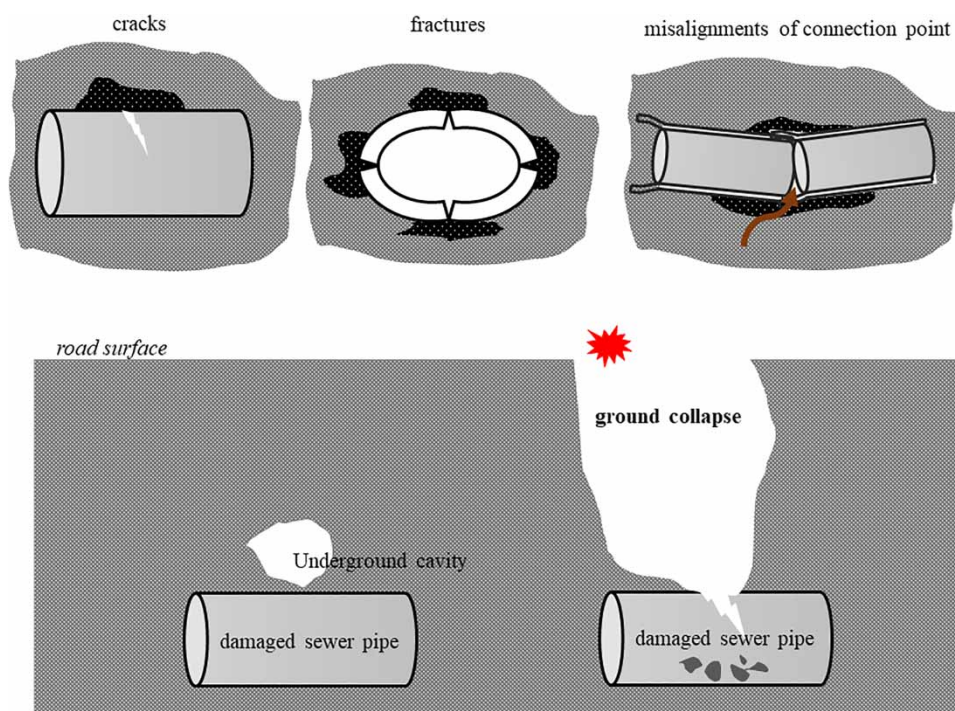


Figure 1 | Schematic representation of sinkhole caused by a sewer pipe defect.

void forms below the street's paved concrete, the surface may no longer be able to support its weight and collapse into that subterranean space. This may happen suddenly, or gradually, and its development may be aggravated under heavy rainfall.

In the past, a risk management model, as [Motteff \(2005\)](#) proposed, was adopted to protect the public infrastructure, assessing the risks of infrastructure through the integration of information such as threats, vulnerabilities, and consequences. [Motteff \(2005\)](#) tried to find ways to reduce risks, determine the priority of risk reduction measures, and improve the critical infrastructure system security to resist destructive events. The risk management model focuses on the design of robust critical infrastructure, and minimizes the probability of risk events and their consequences through a series of preventive and protective measures. However, most critical infrastructures cannot withstand all potential disruptive events ([Mottahedi et al. 2021](#)). On September 25, 2015, 17 Sustainable Development Goals (SDGs) were formally adopted at the 70th United Nations Sustainable Development Summit. The ninth goal, in order to reflect the society that can effectively deal with the increasing number of man-made and natural disasters, emphasizes the establishment of resilient infrastructure. In previous studies on the resilience of water resources systems and urban drainage systems (UDS), [Maier et al. \(2001\)](#) developed an efficient method for estimating the risk-based performance measures reliability, vulnerability, and resilience, which is based on the First-Order Reliability Method (FORM). [Maier et al. \(2001\)](#) extended the definitions of these three performance measures in previous studies, defined reliability as the frequency that a system is in a satisfactory state, and defined vulnerability as the likely magnitude of failure, if a failure occurs. The resilience was defined as the inverse of the expected value of the length of time that a system's output remains unsatisfactory after a failure. [Butler et al. \(2014\)](#) introduced 'Safe & SuRe', a new water resource management method, and in particular, discussed the concept of resilience as a way of managing system failures and defined resilience as the degree to which the system minimizes level of service failure magnitude and duration over its design life when subject to exceptional conditions. At the same time, they defined sustainability as the degree to which the system maintains levels of service in the long term while maximizing social, economic and environmental goals. They believe that reliability is the bedrock of the Safe & SuRe concept, and is the core business of the water sector. Sustainability is predicated on a long-term horizon, so that resilience is a key underpinning concept in operationalizing sustainability. They suggested that further work is needed to develop quantifiable indicators of general resilience. [Casal-Campos et al. \(2018\)](#) defined and quantified these key concepts such as reliability, resilience, and sustainability for a number of gray, green and hybrid strategies, aimed at improving the capacity issues of an existing integrated urban wastewater system. [Binesh et al.](#)

(2019) introduced a new definition of the sustainability of UDS as a key infrastructure to control urban flooding. The goal is to examine the effectiveness of implementing best management practices in reducing urban flooding, and measuring the degree of system efficiency through four indicators: reliability, robustness, improvability, and adaptability. Among them, robustness, improvability, and adaptability are considered as the basis of the resilience characteristic of the system. Bakhshipour *et al.* (2021) introduced a multicriteria decision-making platform for sustainable planning of urban drainage infrastructures considering centralized or decentralized strategies. The platform is based on simple reliability, resilience and sustainability indices.

In summary, it can be seen that previous studies basically agree with a pyramid that explains the connection between reliability, resilience, and sustainability introduced by Butler *et al.* (2014). The pyramid can indicate that resilience should be based on reliability and sustainability should be based on resilience. Therefore, disaster-risk reduction should not only focus on reducing the possibility of disasters, but also on improving resilience to disasters. Sustainability and resilience are mutual concepts: more sustainability leads to more resilience, more resilience leads to more development, and this development leads to more sustainability. Reducing disaster-risks by strengthening resilience has laid a foundation for achieving SDGs. Critical infrastructure has gradually shifted from robust design to resilience design, with more emphasis on preparation, response, and recovery for disruptive events. Considering the importance of resilience in infrastructure management, this study aims to establish a framework to evaluate sewer network resilience indices considering the risk of ground collapse (GCR, ground collapse-resilience), so as to further improve the service level of sewers.

The word ‘resilience’ originates from the Latin word ‘resiliere’, which means the concept of ‘bounce back’ in physics. In the field of infrastructure construction, the term is used in many applications. When studying the ability and performance of infrastructure under disaster conditions, people are more accustomed to calling it resilience. Most infrastructure systems serve humans and have specific functions. Therefore, the resilience of infrastructure can be defined as the ability of the system to maintain its original function and reduce failure damage when subjected to external shocks (Attoh-Okine *et al.* 2009; Almoghatawi *et al.* 2019). Critical infrastructure networks such as electric power, water supply and drainage, natural gas, telecommunications, and transportation provide the services necessary for the continuous operation of society and are the backbone of modern societies.

Generally, the evaluation procedures of resilience can be divided into two categories: qualitative and quantitative. Many researchers are using the concept of resilience to study the system performance in response to external interference, but the quantitative evaluation of resilience is very limited (as shown in Table 1). Recent studies on the methods for quantifying resilience mainly include: (1) the standardized shadow area under the system performance function curve; (2) the topology measurement; (3) the ratio of the failure probability to the recovery probability, etc.

In the application of resilience concepts and quantitative methods related to urban water systems, Mugume *et al.* (2015a) proposed that the future urban water systems need to be designed in terms of resilience and reliability to cope with more complex social environments and climate change. To improve the performance of the system considering resilience and reliability simultaneously, it is necessary to make improvements in terms of flexibility and redundancy. However, this article only verifies the measures to improve the resilience of the urban water system by establishing a simple scenario simulation in the virtual pipe network system, which is far from the complex situation of resilience in reality. In the application of resilience concepts and quantitative methods related to UDS, Bakhshipour *et al.* (2021) defined the urban drainage system and determined the performance indicators of the system, based on simple reliability, resilience and sustainability indices, formulated a multi objective optimization problem to simulate the optimization system, so as to obtain the final decision making. In the case study, both functional resilience and structural resilience are considered, and the quantitative calculation formula is shown in Table 1. Although their proposed framework is promising in handling many decisions, objective functions, and indicators for designing sustainable UDSs, they did not manage to solve the required high computation effort problem.

The qualitative assessment methods of resilience are mainly divided into the form of conceptual frameworks and semi-quantitative indices. The conceptual framework provides insights into the concept of resilience, but does not provide quantitative value. Semi-quantitative method usually involves summarizing expert opinions along multiple dimensions into one index (Hosseini *et al.* 2016). However, as the urban infrastructure, the sewer network resilience is rarely evaluated, and the existing studies mainly consider the perspective of earthquake prevention and flood prevention. Bruneau *et al.* (2003) and Chang & Shinozuka (2004) determined the four properties of resilience (4Rs): robustness, rapidity, redundancy, and resourcefulness. Robustness refers to the strength, or the ability of components, systems, and other analysis units to withstand a given level of stress or demand without degradation or loss of function. Rapidity refers to the ability to meet priorities and achieve goals in a timely manner to control losses and avoid future interruptions. Redundancy refers to the degree to which

Table 1 | Research related to methodologies of quantitative resilient assessments

References	Equations for resilience assessment	Variables
Bruneau <i>et al.</i> (2003)	$RL = \int_{t_0}^{t_1} [100 - Q(t)]dt$	RL: Resilience Loss Q(t): A quality function that measures the system performance as a percentage t ₀ : The time of the disruption occurs t ₁ : The time at which the resilience is calculated
Chang & Shinozuka (2004)	$R = Pr(A i) = Pr(r_0 < r^* \text{ and } t_1 < t^*)$	R: Resilience Pr: Probability A: Setting standard i: Scale of disaster r ₀ : Initial loss r*: Max allowable loss t*: Max allowable time
Vugrin & Camphouse (2011)	$RDR = \frac{\int_{t_0}^{t_1} TSP(t) - SP(t) dt + \alpha \int_{t_0}^{t_1} RE(t) dt}{\int_{t_0}^{t_1} TSP(t) dt}$ $OR = \min_{RE} \frac{\int_{t_0}^{t_1} TSP(t) - SP(t) dt + \alpha \int_{t_0}^{t_1} RE(t) dt}{\int_{t_0}^{t_1} TSP(t) dt}$	RDR: Resilience cost index related with specified recovery effort OR: Optimal resilience cost index TSP: Target value of system performance SP: Present system performance RE: Recovery effort α: Weighted number
Henry & Emmanuel Ramirez-Marquez (2012)	$\mathcal{R}_F(t_r e_j) = \frac{F(t_r e_j) - F(t_d e_j)}{F(t_0) - F(t_d e_j)} \quad \forall e_j \in D$	$\mathcal{R}_F(t_r e_j)$: The value of resilience F(t _r e _j): The figure-of-merit e _j : Disruptive event D: Disruptive events set
Mugume <i>et al.</i> (2015b)	$Res_0 = 1 - \frac{V_{TF}}{V_{TI}} \times \frac{t_f}{t_n}$	Res ₀ : The resilience index V _{TF} : The total flood volume V _{TI} : The total inflow into the system t _f : The mean duration of nodal flooding t _n : The total elapsed (simulation) time
Bakhshipour <i>et al.</i> (2021)	$Res_{Functional} = 1 - \frac{V_{flooding}}{V_{runoff}} \times \frac{T_{flooding}}{T_{Simulation}}$ $Res_{Structural} = \frac{\sum_{i=1}^{NP} 100(1 - (A_i/A_T))\%}{NP}$	Res _{Functional} : Functional resilience V _{flooding} : Total water that overflows the nodes V _{runoff} : Total runoff volume T _{flooding} : Spatial average flood duration computed for all flooded nodes in the system T _{Simulation} : Total simulation time A _i : Area connected to pipe i A _T : Total area

there are replaceable elements, systems, or other analysis units, that is, the ability to meet functional requirements in the event of interruption, degradation, or loss of function. Resourcefulness is the ability to identify problems, establish priorities, and mobilize resources when there are conditions that may damage an element, system, or other analysis units. Generally, the evaluation of the four attribute dimensions of resilience involves various factors with different measurement units, which can introduce uncertainties and complexities in the evaluation process. To overcome this limitation, a qualitative approach can be applied using multi criteria decision-making (MCDM) techniques. In MCDM techniques, multiple experts can decide the weights of the 4Rs and various factors of them and evaluate each of them. [Orencio & Fujii \(2013\)](#) used the analytic hierarchy process (AHP) to determine the criteria and elements that can be used to reduce the vulnerability of coastal communities, and proposed a local disaster-resilience index to assess coastal communities, which can be used as a tool for local governments to facilitate meaningful disaster-risk reduction and management. [Patel *et al.* \(2020\)](#) used the AHP to obtain the relative weight value of each element of the bridge resilience index. By evaluating the resilience of bridge, it is helpful to formulate management, maintenance and improvement strategies. [Haque *et al.* \(2018\)](#) used subjective approach to analyse the cyber resilience property of industrial control systems (ICS) in the events of cyberattacks. A comprehensive cyber resilience framework for the ICS was proposed by decomposing the resilience metric into a hierarchy of several sub-metrics. Therefore, this study also uses the AHP and the weighted sum method (WSM) to develop a resilience evaluation

methodology for sewer networks. AHP is used to determine the weights of evaluation indices at all levels. WSM aggregates the 4Rs to determine sewer network resilience. The sewer network resilience index (SRI) is a function of determination of the factors associated with the 4Rs, framing their structure, and sound subjective judgments. Therefore, the SRI represents the degree of resilience of the sewer networks. In order to deal with frequent ground collapse accidents caused by damaged sewer pipes, the objectives of this study are: (1) to prepare a hierarchical structure by identifying various factors that prioritize sewer network resilience, (2) to develop an evaluation process to determine the SRI, (3) to evaluate the resilience of sewer networks, and (4) to illustrate the practical applicability of the SRI.

METHODS

Ground subsidence response procedure

Before identifying the indices under the four-dimensional attributes of sewer network resilience in the case of ground subsidence, it is necessary to understand the general response procedures when ground subsidence occurs. Figure 2 shows the response procedure for ground subsidence proposed by the Ministry of Environment of South Korea.

This study uses the performance criteria (4Rs) of resiliency presented by Bruneau *et al.* (2003). Thirteen new factors are identified from the existing literature review on sewer resilience and interviews with sewer experts. Therefore, a new hierarchical structure that prioritizes the resilience of sewer networks is developed to assess the SRI as shown in Figure 3. The following section on the identification and determination of factors introduces the identification process of each factor and the value process of the relevant factors used in the case study. In the section on weights calculation through AHP procedures, the calculation process of the weight value of each factor in this study is introduced. In the case study section, based on the weight values of each factor obtained by the AHP procedures and the estimated values of related factors used in the case study, the weighted sum method is used to calculate the final resilience index value of the sewer networks that is the object of the case study. At the same time, through the division of resilience index value, the level of resilience of the current sewer networks under the background of responding to the urban ground collapse is determined.

Identification and determination of factors

The framework is a holistic framework for assessing SRI. As shown in Figure 3, the factors to resiliency terms are partitioned into the first level: 4Rs, and the second level: the factors corresponding to 4Rs. All factors with each of the 4Rs are briefly discussed below.

Rapidity

Rapidity is defined as the ability to control losses and avoid future disruption, meet priorities and achieve goals in a timely manner (Bruneau *et al.* 2003). The sewer network's level of service should return to normal as soon as possible. Then, to measure the rapid restoration of the sewer network, the factors that need to be considered are:

Ra1: Allowable Restoration Time. Allowable restoration time refers to the time required for restoration work to return the sewer network to its full and normal working condition. For example, the Seoul Metropolitan Government has always applied the one-day restoration principle when repairing sewer pipes. The traffic volume in the center of Seoul is very large, so most of the construction of sewer pipes causes traffic jams. To minimize traffic congestion, it is recommended to repair or replace at night than during the daytime. When the repair work cannot be completed at the night, the surface of the street is covered temporarily with light-weight lining boards to allow traffic to flow again during the daytime, and construction will be restarted at next night. It is assumed that the allowable restoration time required to recover the original sewer service level would normally be within one day, i.e. within 24 hours. However, when ground collapse occurs due to damaged sewer pipes, the repair of the sewer pipes usually takes an excavation method, so it takes a relatively longer time than the trenchless method. In this study, the restoration time was classified into different levels, which are described in Table 2.

Ra2: Accessibility. The accessibility to areas where ground collapse accidents may occur will also affect the restoration speed. Limited accessibility to infrastructure can potentially delay the repair process and cause greater damage to surrounding assets (Mazumder *et al.* 2021). Accessibility can be hampered by narrow or no easements, deep infrastructure, and difficult or limited vehicle access (Shahata 2013). An easement refers to a kind of usufructuary right of

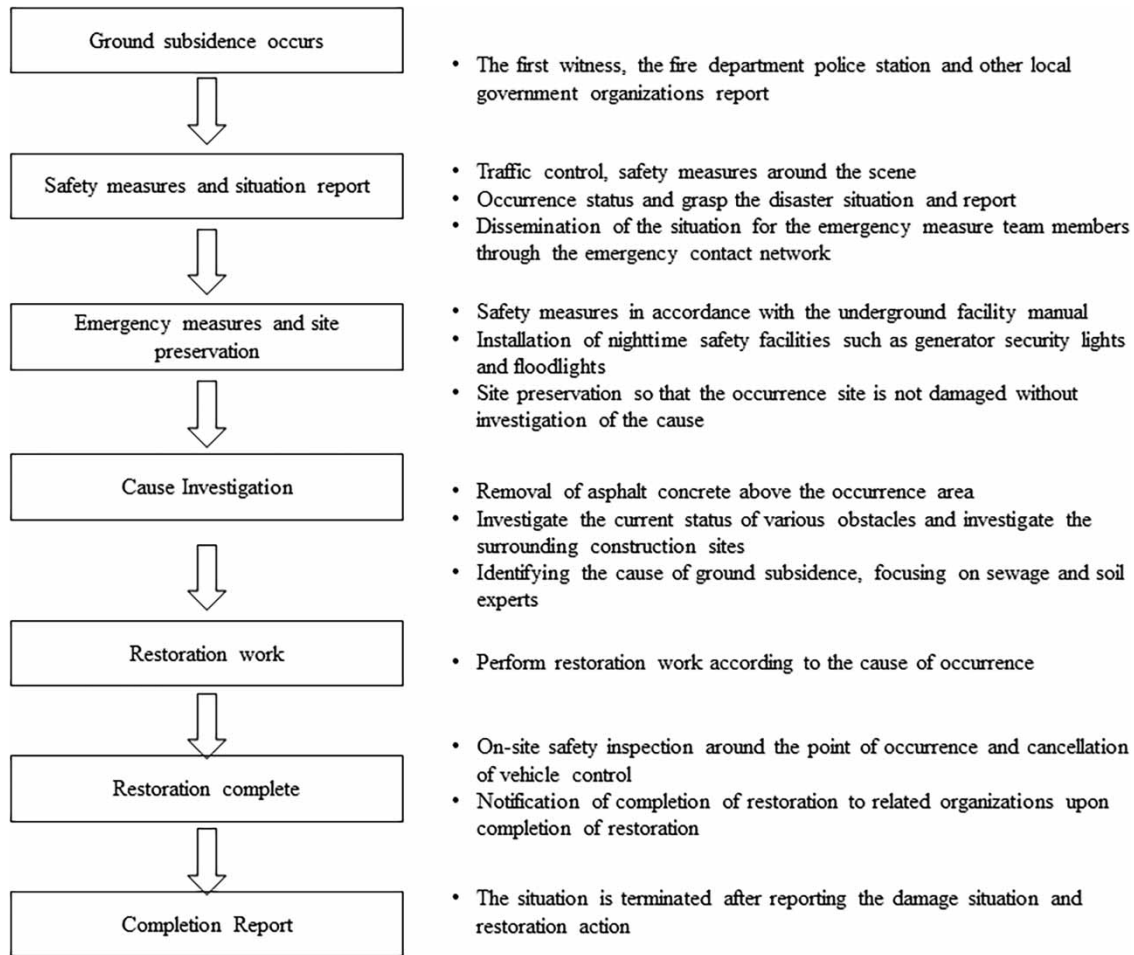


Figure 2 | Response procedure in case of ground subsidence (MOE 2015).

land that the person who owns the land uses other people's land for a specific purpose, and ultimately enhances the value of their own land use. In this study, it is assumed that there is no easement due to the complexity of the easement issue. In addition, the underground space includes sewer pipes, and various underground facilities such as water supply, electricity, communications, gas, and district heating are buried like spider webs. As the sewer pipelines are frequently damaged during construction, the Seoul Metropolitan Government has promoted the establishment of management standards to ensure that other underground facilities maintain a separation distance of at least 0.3 metres from sewer pipelines. Maintaining an appropriate distance between underground facilities can protect the sewer pipes from other infrastructures during construction to fundamentally prevent secondary accidents such as road subsidence, and to secure the necessary distance in case of future excavation and improvement. In this study, in order to evaluate the accessibility of the eight small blocks selected for evaluation, the accessibility was evaluated indirectly by using the Seoul sewer GIS data to calculate the average buried depth of the sewer pipes in each small block. If the burial depth is low, due to its relatively high accessibility, the sewer pipes can be excavated or replaced more quickly in an accident. Table 2 divides accessibility into several levels based on the average buried depth.

Ra3: Department Cooperation Plan. In addition to sewer pipes, underground facilities also include infrastructures such as water supply pipes, gas pipelines, communication pipes, subways, and other infrastructure facilities. Ground collapse accidents caused by damaged sewer pipes may also cause damage to other surrounding infrastructures. Therefore, during the restoration work, the various departments should cooperate, which can not only save costs (especially the cost of

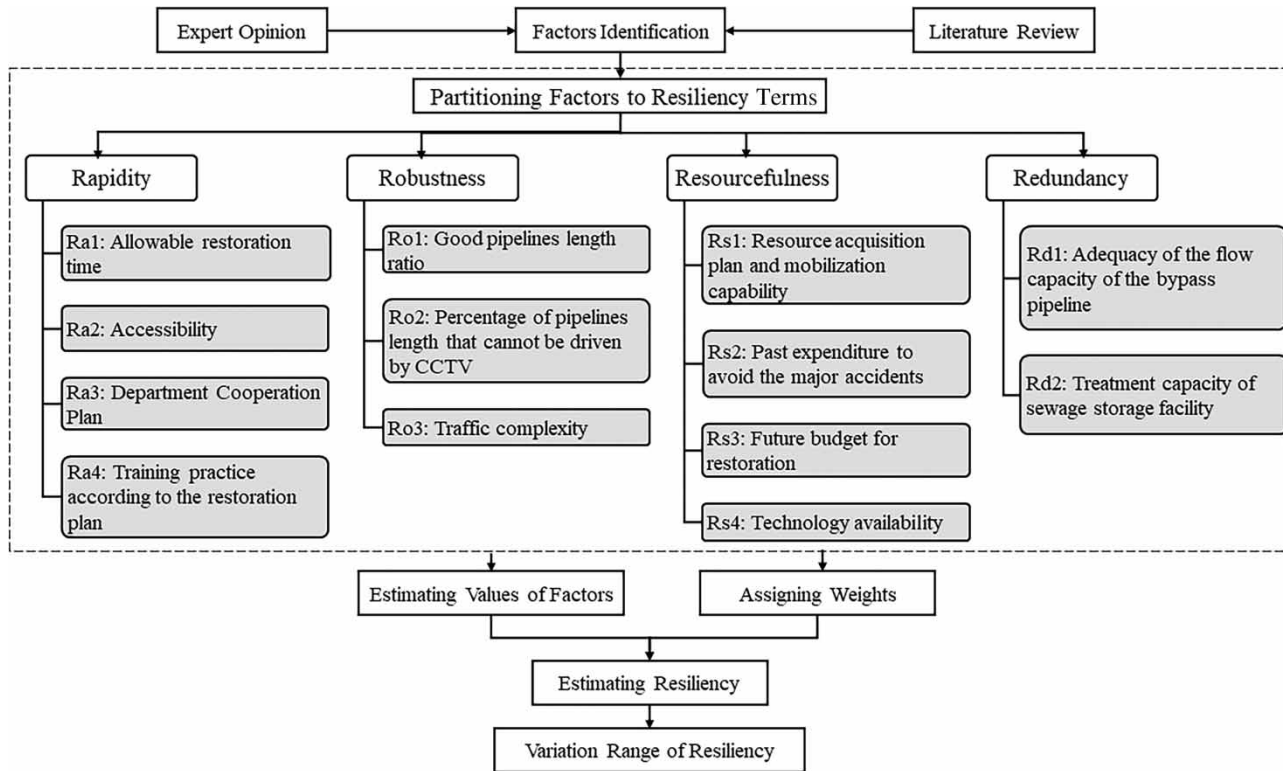


Figure 3 | Proposed framework for quantifying resiliency of sewer networks.

Table 2 | Proposed levels for some subdivision factors of the evaluation object

Level	Allowable restoration time (days)	Average buried depth (m)	Traffic complexity (number of intersections/ha)	Past expenditure to avoid the major accidents (one million won/km)
10% (Very Low)	>7 days	>2.0	>0.9	<10
20% (Very Low to Low)	6–7 days	1.8–2.0	0.8–0.9	10–15
30% (Low)	5–6 days	1.6–1.8	0.7–0.8	15–20
40% (Medium Low)	4–5 days	1.4–1.6	0.6–0.7	20–25
50% (Medium)	3–4 days	1.2–1.4	0.5–0.6	25–30
60% (Medium High)	2–3 days	1.0–1.2	0.4–0.5	30–35
70% (High)	1–2 days	0.8–1.0	0.3–0.4	35–40
80% (High to Very High)	0.5–1 day	0.6–0.8	0.2–0.3	40–45
90% (Very High)	0.25–0.5 day	0.4–0.6	0.1–0.2	45–50
100% (Extremely High)	<0.25 day	<0.6	<0.1	>50

excavation and surface reconstruction) and time, but also minimize nuisances for example due to repeated road closures for different infrastructure restorations (Tscheikner-Gratl *et al.* 2016).

Ra4: Training Practice According to the Restoration Plan. Proactive planning allows sewer managers to plan long before emergencies or disasters occur, for example by specifying who should be responsible for the work. Responding to emergencies in sewerage systems calls for the participation of the company's technical and operational units and the various support units, as well as from representatives of other organizations involved in environmental health and hazard management (WHO 2002). In the asset management of infrastructure, vulnerability assessment is usually carried out, and

the next step is to determine the most effective prevention and mitigation measures. These measures must include devising emergency operations, allocating input manpower, materials, and other resources, and preparing and carrying out the necessary training activities. Relatively speaking, areas with restoration plans and training plans can recover functionality faster.

Robustness

Robustness refers to categorical strength or resistance to disruptions. Robustness can be defined as strength, or the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function (Bruneau *et al.* 2003). The following factors to measure the robustness of sewer networks are considered:

Ro1: Good Pipelines Length Ratio. Sewer pipes age and deteriorate over time, and their condition and performance need to be effectively monitored to improve robustness (Angkasuwansiri & Sinha 2015). Existing sewer system evaluation technologies include closed-circuit television (CCTV), infrared thermal imaging systems, acoustic distance measurement methods, ground-penetrating radar, and other advanced systems (KARO, PIRAT, SSET), etc. (Wirahadikusumah *et al.* 1998). Among them, CCTV is the most commonly used for sewer pipe inspections. Currently, the interpretation of closed-circuit television images to identify the types and locations of pipeline defects is mostly conducted manually, which is time consuming and labour intensive, and its accuracy is not very high. Therefore, the research on the automatic detection method of sewer pipe defects using computer deep learning technology is constantly developing, so that the sewer pipe defects can be detected more accurately and faster (Yang & Su 2008; Cheng & Wang 2018; Moradi *et al.* 2019). In order to prevent ground subsidence caused by aging and poor sewers, the Ministry of Environment of South Korea proposes to conduct detailed investigations on areas where ground subsidence may occur. The inspection method is based on CCTV investigation, supplemented by visual investigation, and GPR or endoscope investigation increases when necessary. The structural and operational conditions of the sewer pipes are judged and evaluated by the defect levels. This study used data from the 2030 Master Plan on Sewerage Rehabilitation (Seoul, 2018) to obtain the good pipelines length ratio in the area to be evaluated. As explained above through CCTV investigation, it is possible to judge the robustness of the sewer pipes in different small blocks by using data on the length of old defective pipelines judged according to the structural and operational conditions level and the length of the entire pipelines in the evaluation area. Using the information in Table 3, the good pipeline length ratio calculation formula is:

$$\text{Good pipeline length ratio} = \frac{(\text{Length of entire pipelines} - \text{Length of old defective pipelines})}{(\text{Length of entire pipelines})} \quad (1)$$

Ro2: Percentage of Pipelines Length that cannot be driven by CCTV. When using closed-circuit television to inspect sewers, if the vertical displacement of the pipe axis exceeds 25% of the pipe diameter, resulting in a step difference, the CCTV inspection equipment will not be able to drive through the sewer pipe. Therefore, if the pipeline section cannot be driven due to CCTV inspection equipment in the sewer pipes investigation, and other supplementary inspection measures are not taken, the condition of the uninspected pipe section cannot be grasped, the probability of failure is relatively high, which affects the robustness of the sewer network. In this study, the sections where unable to drive CCTV may be caused by high water level, soil deposition, or other obstacles, etc. Accessibility to manholes is also constrained by poorly maintained manhole lids, obstructions installed above manhole without permission, irretraceable manhole lids, and vehicle parking above manhole. The investigation vehicles cannot often approach the sites due to narrow roadways, traffic congestion, traffic control sections, industrial or commercial districts, and private areas. This study used the data on the length of pipelines that cannot be driven by CCTV and the length of entire pipelines in the evaluation area (consultation data with Seoul Water Reclamation Planning Division and Sewerage Statistics) as shown in Table 3. Using the information in Table 3, the percentage of pipelines length that cannot be driven by CCTV calculation formula is:

$$\text{Percentage of pipelines length that cannot be driven by CTV} = \frac{(\text{Length of pipelines that cannot be driven by CCTV})}{(\text{Length of entire pipelines})} \quad (2)$$

Table 3 | Detailed indicators related to the evaluation object

Evaluation area	Length of old defective pipelines (m)	Length of pipelines that cannot be driven by CCTV (m)	Length of the pipelines for lack of hydraulic capacity (m)	Length of entire pipelines (m)
Block A	20,501	289.49	638	42,277
Block B	6,127	488.2	2,722	17,697
Block C	3,385	1,330.32	198	7,167
Block D	891	0	0	1,782
Block E	1,479	0	1,196	5,350
Block F	1,501	0	420	3,843
Block G	9,640	316.33	566	20,413
Block H	19,743	0	1,520	42,525

Ro3: Traffic Complexity. Sewer pipes are basically buried on public roads. In principle, the minimum soil thickness of the pipeline should be one metre, and if the vibration is inevitably affected by the arterial road or wheel load in places where soil thickness is unavoidably reduced, the design standards are specified to review the safety of the pipeline, replace with high-strength pipes, reinforcement or protective work. If these sewer design standards are not strictly applied, damage to sewer pipelines can be exacerbated when traffic complexity is high, and the robustness of sewer networks in areas with high traffic complexity can be considered relatively low. In this study, we indirectly evaluated the traffic complexity of the area designated as the number of intersections in the zone unit area (see [Tables 2 and 4](#)) because it was difficult to obtain traffic data directly from the zone under evaluation.

Resourcefulness

Resourcefulness is the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some element, system, or other units of analysis; resourcefulness can be further conceptualized as consisting of the ability to apply material (i.e., monetary, physical, technological, and informational) and human resources to meet established priorities and achieve goals ([Bruneau et al. 2003](#)). In short, it refers to the ability to identify problems and priorities, mobilize and maximize available resources. Therefore, to achieve better resilience of the sewer network, more resources are required. The following factors can be considered to measure the resources of the sewer network:

Rs1: Resource Acquisition Plan and Mobilization Capability. Resource planning is an indispensable part of project management. Project management can be strengthened through the three steps of determining required resources, obtaining resources, and managing resources. The resources generally required in a sewer network restoration project include manpower, materials, equipment, facilities, and other resources. In an ideal situation, all project resources will be available, but in reality, resource planning must consider the acquisition of resources. Once resources are obtained and available to perform project work, they must be managed to ensure that they contribute at the highest level of performance. The Seoul Metropolitan Government is responsible for the maintenance, operation, and management of sewer pipes for each local autonomous district. However, even if a specific autonomous district is insufficient in securing and supplying resources due to a ground subsidence accident, it is thought that Seoul Metropolitan Government's Water Reclamation Planning Division can mobilize surplus resources from other autonomous districts. It can also be assumed that sufficient management and coordination capabilities are secured to support them.

Rs2: Past Expenditure to Avoid the Major Accidents. To avoid accidents, the expenditures for maintenance and management of sewer pipes in the past can reflect a certain degree of financial independence. In general, a huge budget is required to carry out the urban sewer pipeline rehabilitation project. Therefore, by classifying various drainage areas and subareas, and small blocks in the city, the risk level is prioritized through the condition evaluation of the pipeline, and the

Table 4 | Summary of subdivision factors for evaluation object

Sub-factors	Unit (s)	Block A	Block B	Block C	Block D	Block E	Block F	Block G	Block H
Ra1: Allowable restoration time	Day	1	1	1	1	1	1	2	1
Ra2: Accessibility (average buried depth)	m	1.1872	0.8497	1.1503	1.1479	1.0000	1.8223	0.7986	0.8619
Ra3: Department cooperation plan	(Y/N)	Y	Y	Y	Y	Y	Y	Y	Y
Ra4: Training practice according to the restoration Plan	(Y/N)	Y	Y	Y	Y	Y	Y	Y	Y
Ro1: Good pipelines length ratio	%	52%	65%	53%	50%	72%	61%	53%	54%
Ro2: Percentage of pipelines length that cannot be driven by CCTV	%	1%	3%	19%	0%	0%	0%	2%	0%
Ro3: Traffic complexity	Number of intersections/ha	0.27	0.17	0.45	0.19	0.06	0.16	0.10	0.11
Rs1: Resource acquisition plan and mobilization capability	(Y/N)	Y	Y	Y	Y	Y	Y	Y	Y
Rs2: Past expenditure to avoid the major accidents	One million won/km	20.85	53.51	27.48	9.73	7.28	59.44	38.51	44.78
Rs3: Future budget for restoration	%	90%	80%	80%	80%	80%	80%	80%	70%
Rs4: Technology availability	%	60%	60%	60%	60%	60%	60%	60%	60%
Rd1: Adequacy of the flow capacity of the bypass pipeline	%	98%	85%	97%	100%	78%	89%	97%	96%
Rd2: Treatment capacity of sewage storage facility	m ³	320,000	150,000	0	0	0	0	0	0

pipeline rehabilitation project is carried out sequentially as soon as the budget is secured. Even if pipeline rehabilitation is performed in some areas, it may be difficult to see that perfect pipeline rehabilitation is achieved because decisions such as pipeline replacement after excavation, cured-in-place pipe (CIPP) repair, and point repair are made depending on the level of defects. If a certain amount of pipeline rehabilitation work has been carried out before the ground subsidence accident, it can be estimated that fewer resources will be required to recover when a ground subsidence accident occurs in or near the relevant area. It would be possible to reduce the possibility of a large-scale subsidence accident. In this study, the past expenditure to avoid the major accidents was evaluated using the operation maintenance cost of sewer pipes spent for each small block over the past three years (2017–2019) divided by the length of entire pipelines in the evaluation area. The specific results are shown in Table 4. Based on this, the past expenditure to avoid the major accidents is classified into several levels, as shown in Table 2 below.

Rs3: Future Budget for Restoration. Funding arrangement refers to the adjustment of the financial budget for maintenance and reconstruction work. Adjustments are only needed if the available budget is tight. Therefore, this factor is important for resiliency planning because it will reduce the pressure on the available budget and maximize the options for sewer managers to respond to the consequences of acute shocks. Secured budget for acceptable restoration costs to restore to the original level of service is used to evaluate the resourcefulness. According to the Seoul Metropolitan Government's 2030 Master Plan on Sewerage Rehabilitation, sewerage rehabilitation plans are established for the target areas of this study, and eight small blocks are presented separately in 2020, 2025, and 2030. This study assumed that the sewerage rehabilitation plan is 2020, the assurance rate of the future budget for restoration is 90%, 2025 is 80%, and 2030 is 70%, and it is presented in Table 4.

Rs4: Technology Availability. Resource availability is critical to the success of the project plan. When managers clearly know which manpower can accept tasks, which materials, equipment, technology, and how much budget can be applied to the project, they can plan the project accurately. Previously, the resource acquisition plan indicators involved

manpower, materials, equipment and other resources, and the future budget for restoration indicator made a budget assessment of restoration cost. Besides, the availability of technology to quickly and safely restore the original state from the subsidence of the foundation can also be considered. In the event of the collapse of sewer pipes, it is essential to prevent connected household or serviced areas from discharging wastewater or to use bypass pipes. Bypassing technology in temporary work is an important one to let, especially a large amount of wastewater to discharge through urgently installed bypass pipes, pumps, and other equipment. In addition, various physical and chemical technologies are required, i.e., the use of alternative soil to restore the bearing capacity of soil weakened by ground subsidence or permeation grouting by the injection of soil hardeners. In order to identify the status of spots that are difficult to access or visually observe, advanced technologies such as ground-penetrating radar and CCTV investigation using endoscopes, and rapid sewer repair and pavement technologies are essentially required as well. In this study, when determining the degree of technology availability, technology-related information can be shared under the jurisdiction of the Seoul Metropolitan Government, so it can be assumed that the technology availability of each small block is the same. In addition, although it is an era when various cutting-edge smart technologies such as the fourth industrial revolution technology are widely used, once a ground collapse accident occurs, construction must be carried out mainly by manpower and equipment-intensive operations. Therefore, the technology availability of each small block was assumed to be 60% less than 100%.

Redundancy

Redundancy refers to the reliance on multiple supplemental or repeating services to sustain the sewer network functionality, operations, and management in the event that some services become critically disrupted (Bruneau *et al.* 2003). In order to achieve better resilience, more substitutable elements and components are required. The following factors are considered to measure the redundancy of the sewer network:

Rd1: Adequacy of the Flow Capacity of the Bypass Pipeline. Due to urban expansion and development, the runoff coefficient will increase accordingly, and the planned stormwater runoff may increase, which may result in the insufficient capacity of the existing sewage pipeline. When the bypass pipeline has a large sewage flow capacity, it can bear a certain amount of sewage that should have been transferred by the pipe section damaged by ground subsidence. In this study, using the pipeline length and hydraulic capacity data of the area to be evaluated, the adequacy of the flow capacity of the bypass pipeline was expressed as the ratio of the length of the pipelines for lack of hydraulic capacity to the length of the entire pipelines (refer to Table 3 and Table 4).

Rd2: Treatment Capacity of Sewage Storage Facility. In addition to the availability of bypass pipelines, the existence of sewage storage facilities can also further increase the redundancy of the sewer network (Dong *et al.* 2017; Juan-García *et al.* 2017). A sewage storage facility also plays a role to reduce the discharge of pollutants in sewage flowing into sewer pipelines to rivers, seas and other public water bodies, and temporarily store sewage or eliminate or to reduce pollutants by sending sewage to wastewater treatment plants after completing restoration work. In this study, the treatment capacity of the sewage storage facility present in the evaluation area is shown in Table 4. Among them, Block A has 320,000 cubic metres, which is estimated to be 90% after consultation with sewer experts. Block B has 150,000 cubic metres, which is about 60%. In addition, the other six small blocks have no sewage storage facility at all.

Weights calculation through AHP procedures

In summary, the selected factors related to 4Rs are presented and how they affect the sewer network resilience are briefly explained. This study uses the AHP to propose a weighting system for each dimension of the 4Rs and each factor of them. Pairwise comparison is used in the questionnaire to collect opinions from different experts. It is the core of the AHP (Saaty 1994), the basis of its judgment is Saaty's nine-point scales, as shown in the following Table 5. The higher number indicates that the selected factor is largely considered more important than the other factors compared (Saaty 1999). The basic steps of the AHP approach are briefly described below:

Step 1: Establish a hierarchical structure. The structure starts from the top (objective), middle orders (criteria and sub-criteria), and then placed (alternatives) at the bottom level. A hierarchical structure of the sewer network resilience has been developed for the calculation of the weight for the factors as shown in Figure 3.

Table 5 | Adapted from Saaty's nine-point scale (Saaty 1994; Saaty 2008)

Comparison intensity	Definition	Explanation
1	Equally important	Two decisions equally influence the upper-level objective
3	Moderately more important	One decision is moderately more favorable for the upper-level objective fulfillment
5	Strongly more important	One decision is strongly more favorable for the upper-level objective fulfillment
7	Very strongly more important	One decision is significantly more favorable for the upper-level objective fulfillment
9	Extremely more important	The difference between influences of the two decisions is extremely significant
2, 4, 6, 8	Intermediate judgment values	When a compromise is necessary to give an intermediary judgment between the previous values

Step 2: Establish a pairwise comparison matrix ($n \times n$) using Saaty's 1–9 relative measurement scale, which is presented in Table 5. The pairwise comparison matrices are determined in terms of which element dominates the other:

$$A = [a_{ij}] = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \dots & 1 \end{bmatrix} \quad (3)$$

where $A = [a_{ij}]$ is a representation of the intensity of the decision maker's preference for one over another compared alternative a_{ij} and for all comparisons $i, j = 1, 2, \dots, n$. Decision-makers facilitate the comparisons of alternative criteria or elements in two rounds until the scores are considered stable. Stability is reached when a certain consensus on a sum of scores is achieved.

Step 3: Compute the importance of pairwise comparison by determining a matrix of the relative rankings for each level of the hierarchy.

Step 4: Compute the consistency index (CI) and the consistency ratio (CR). A CI is evaluated for each of the 4Rs and its factors responded by each expert using

$$CI = \frac{(\lambda_{\max} - N)}{(N - 1)} \quad (4)$$

where $\lambda_{\max}$ is the maximum eigenvalue computed by averaging all individual eigenvalues λ , and N is the number of elements (or criteria) subjected to a priority judgment.

Then, the CR is obtained using

$$CR = \frac{CI}{RI} \quad (5)$$

where RI is the random index (Table 6). Further, the acceptable range of the CR should not be exceeded to 0.10; if it exceeds 0.10 the results are suggested to be inconsistent, and the evaluation process must be reviewed or performed again (Saaty 1994).

RESULTS AND DISCUSSION

Survey overview

A survey was conducted to evaluate the importance of various factors in evaluating the resilience index of sewer networks. For this, 10 sewer experts consisting of four professors, three researchers, and three engineers were selected to participate in the

Table 6 | The order of the random index of consistency with a number of alternatives

Random Index (RI)										
N	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

questionnaire survey. Among the 10 respondents who returned the questionnaire, two had a work experience of fewer than 5 years, two had a work experience of 5 to 10 years, two had a work experience of 10 to 15 years, and four had a work experience of more than 15 years. The questionnaire survey was conducted from August 5, 2021 to August 20, 2021. Ten questionnaires were sent to the survey subjects via e-mail, and a total of 10 questionnaires were collected and all put into analysis.

Analysis of the AHP results

The index weight is a criterion for quantitatively describing the evaluation result. The hierarchical analysis method is adopted, the survey is completed, the opinions of experts are obtained, and the weight of each evaluation index is determined in turn. First, calculate the geometric mean of the values given by each expert on the importance of the pairwise comparison index. The calculation step can be expressed as follows. When 10 experts designate the importance of the pairwise comparison index as $Q_1, Q_2, Q_3, Q_4, Q_5, Q_6, Q_7, Q_8, Q_9, Q_{10}$, the geometric mean $\omega = \sqrt[10]{Q_1 Q_2 Q_3 Q_4 Q_5 Q_6 Q_7 Q_8 Q_9 Q_{10}}$ becomes the comprehensive importance of the pairwise comparison index. When the hierarchical analysis procedure as above is completed, the importance and weight value of each index are provided as shown in Table 7. The evaluation model weight distribution diagram is provided in Figure 4 (absolute weight value).

After the accomplishment of the above AHP steps, the method would provide the importance and weight of each factor. The resilience index of the sewer network can be quantified through the above process. The larger the value, the higher the level of resilience of the sewer network. In addition, benchmark resilience scores are mostly based on 0–1 (Henry & Emmanuel Ramirez-Marquez 2012; Pandit & Crittenden 2016; Assad *et al.* 2019; Chen *et al.* 2020). For example, Patel *et al.* (2020) established a benchmark resilience score between 0 and 1.00 to measure the bridge resilience according to six levels. Scores between 0.90 and 1.00 form the top level, showing excellent resilience, while scores below 0.40 reflect poor resilience. Furthermore, Alshehri *et al.* (2015) recognize a scale of scores between 0 and 5 which can be used to give an overall indication of resilience community in the five levels. These levels are: 5 Very High (81–100%), 4 High (61–80%), 3 Fair (41–60%), 2 Low (21–40%), 1 Very Low (1–20%), and 0 reveals the absence of resilience. Therefore, this study proposes the resilience ranking scale of the sewer network (Table 8) to facilitate quantitative comparison and help sewer network managers manage their assets and enhance their resilience.

Case study

In this study, the sewer networks in eight small blocks of drainage area in Seoul, South Korea were selected as the resilience evaluation object. In Tables 3 and 4, actual values of the sub-factors for eight small blocks are presented. These values were obtained through the 2030 Master Plan on Sewerage Rehabilitation in Seoul metropolitan area (Seoul 2018) and Sewerage statistics data (MOE 2020), as well as the consultation with the Seoul Water Regeneration Plan Division. The final index of sewer network resilience can be evaluated as follows:

$$R = \sum w_i T_{mn} = 0.154T_{11} + 0.065T_{12} + 0.046T_{13} + 0.034T_{14} + 0.253T_{21} + 0.091T_{22} + 0.063T_{23} + 0.056T_{31} + 0.040T_{32} + 0.066T_{33} + 0.018T_{34} + 0.093T_{41} + 0.022T_{42} \quad (6)$$

where, w_i is the weight of each sub-indicator. T_{mn} represents the score of each sub-factor, details can be found in Table 9. $m \in (1, 2, 3, 4)$ means the first-tier evaluation indicator in the order of rapidity, robustness, resourcefulness, and redundancy. $n \in (1, 2, 3, 4)$ means the order of each sub-factor in the second layer. R represents the total score of resilience. For example,

Table 7 | The pairwise comparison matrix, relative importance and priority of 4Rs and sub-factors

4Rs	Rapidity	Robustness	Resourcefulness	Redundancy	Relative importance	Priority
Rapidity	1	0.7375	1.5399	2.7979	0.299	2
Robustness	1.3559	1	2.6094	3.0750	0.406	1
Resourcefulness	0.6494	0.3832	1	1.6693	0.180	3
Redundancy	0.3574	0.3252	0.5991	1	0.115	4
CR	0.0052					
Rapidity	Ra1	Ra2	Ra3	Ra4	Relative importance	Priority
Ra1	1	3.7858	3.0134	3.3470	0.514	1
Ra2	0.2641	1	1.8579	2.2144	0.217	2
Ra3	0.3319	0.5382	1	1.6030	0.155	3
Ra4	0.2988	0.4516	0.6238	1	0.114	4
CR	0.0420					
Robustness	Ro1	Ro2	Ro3	Relative importance	Priority	
Ro1	1	2.7174	4.0941	0.621	1	
Ro2	0.3680	1	1.4051	0.223	2	
Ro3	0.2443	0.7117	1	0.155	3	
CR	0.0005					
Resourcefulness	Rs1	Rs2	Rs3	Rs4	Relative importance	Priority
Rs1	1	1.9348	0.8417	2.1324	0.309	2
Rs2	0.5169	1	0.7140	2.5529	0.220	3
Rs3	1.1880	1.4005	1	4.5695	0.369	1
Rs4	0.4690	0.3917	0.2188	1	0.102	4
CR	0.0318					
Redundancy	Rd1	Rd2	Relative importance	Priority		
Rd1	1	4.2051	0.808	1		
Rd2	0.2378	1	0.192	2		
CR	–					

for Block A, the resilience value was calculated by Equation (7) as follows:

$$\begin{aligned}
 R = & 0.154 \times 70\% + 0.065 \times 60\% + 0.046 \times 100\% + 0.034 \times 100\% + 0.253 \times 52\% \\
 & + 0.091 \times 99\% + 0.063 \times 80\% + 0.056 \times 100\% + 0.040 \times 40\% + 0.066 \times 90\% \\
 & + 0.018 \times 60\% + 0.093 \times 98\% + 0.022 \times 90\% = 0.7509
 \end{aligned}
 \tag{7}$$

Figure 5 shows the resilience values of sewer networks in the selected eight small blocks. The sewage pipe network of Block B shows the highest resilience while Block C shows the lowest resilience, but both show no significant difference in resilience values. Even though the resilience values of the eight small blocks in the same metropolitan area were relatively high with low discrimination power, those values may be varied in greater ranges if the resilience indices proposed in this study are applied to various municipalities. The lower resilience index score of Block C is due to the lower value of ‘good pipe length ratio (first priority)’ and ‘percentage of pipelines length that cannot be driven by CCTV (second priority)’. Therefore, it can be seen that the sewer network of this area should be more thoroughly inspected and rehabilitated in the first place to improve its robustness.

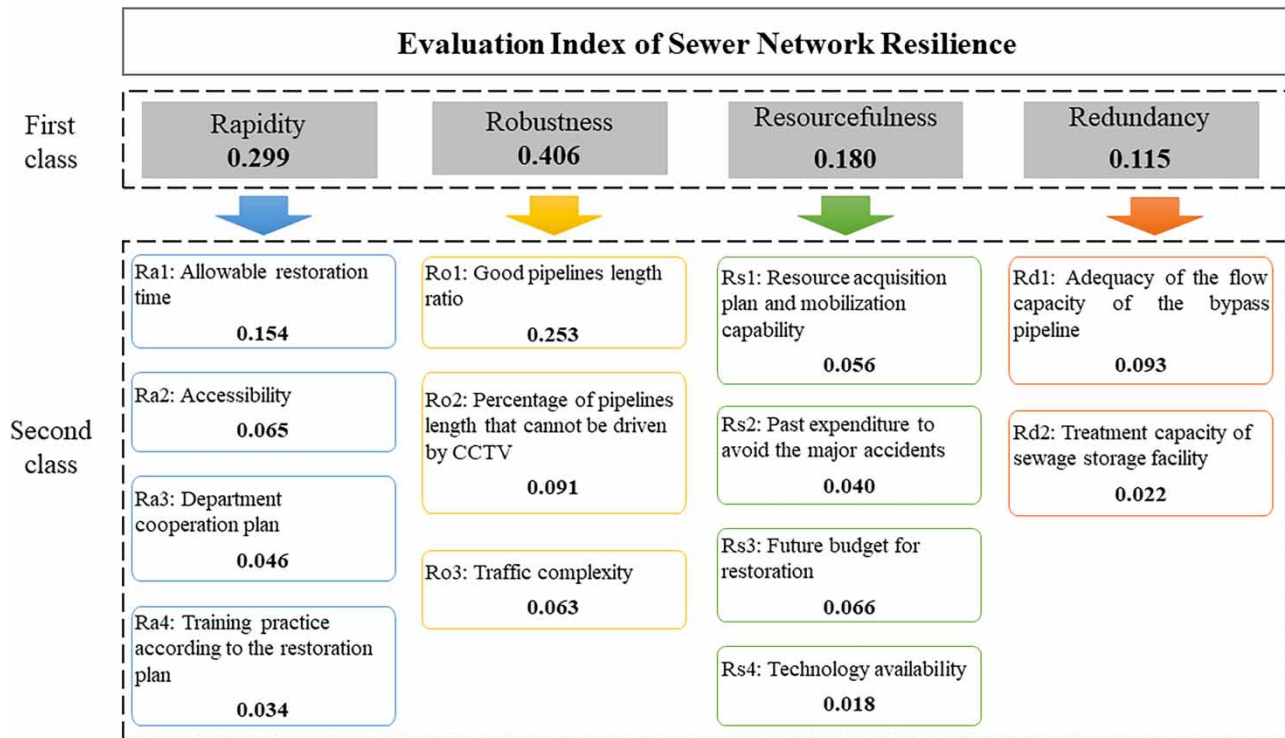


Figure 4 | Evaluation model weight distribution diagram.

Table 8 | Resilience ranking scale of sewer network

Resilience category	Score
Very High	0.80–1.00
High	0.60–0.80
Moderate	0.40–0.60
Low	0.20–0.40
Very Low	0–0.20

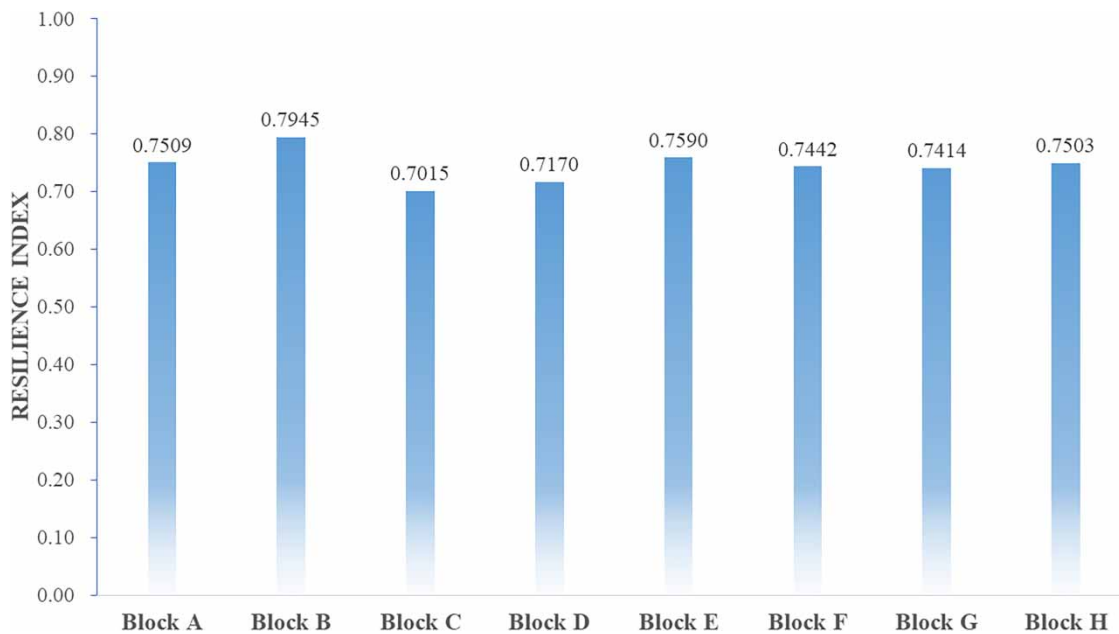
CONCLUSIONS

From the perspective of coping with ground collapse, by identifying and determining factors that affect the resilience of the sewer network, a resilience evaluation system is constructed to quantitatively evaluate the resilience of the sewer networks and to verify the constructed evaluation system through specific examples, the following conclusions are drawn.

The research results showed that the resilience of the sewer network can be quantified by the performance based on the resilience index. Starting from the four basic attributes of resilience, and selecting index elements corresponding to rapidity, robustness, resourcefulness, and redundancy, respectively, the resilience of the sewer network can be better characterized. The priority weights of the four first-level indicators and 13 second-level detailed indicators were determined by applying AHP. WSM is used to calculate the quantitative value of sewer network resilience. Then, the evaluation results of resilience are divided into five stages: 'Very High (I), High (II), Moderate (III), Low (IV), Very Low (V)'. The resilience index evaluation system was applied to eight small blocks of selected drainage areas in Seoul, South Korea, and the results showed that the resilience of the eight small blocks was relatively high. The evaluation index system can scientifically evaluate GCR of sewer network and provide scientific reference for sewer network planning and operation.

Table 9 | Subdivision factors' scores and calculation results of resilience

Sub-factors	Weight of sub-factors, w_i	Block A	Block B	Block C	Block D	Block E	Block F	Block G	Block H
Ra1: Allowable restoration time	0.154	70%	70%	70%	70%	70%	70%	60%	70%
Ra2: Accessibility	0.065	60%	70%	60%	60%	60%	20%	80%	70%
Ra3: Department cooperation plan	0.046	100%	100%	100%	100%	100%	100%	100%	100%
Ra4: Training practice according to the restoration plan	0.034	100%	100%	100%	100%	100%	100%	100%	100%
Ro1: Good pipelines length ratio	0.253	52%	65%	53%	50%	72%	61%	53%	54%
Ro2: Percentage of pipelines length that cannot be driven by CCTV	0.091	99%	97%	81%	100%	100%	100%	98%	100%
Ro3: Traffic complexity	0.063	80%	90%	60%	90%	100%	90%	90%	90%
Rs1: Resource acquisition plan and mobilization capability	0.056	100%	100%	100%	100%	100%	100%	100%	100%
Rs2: Past expenditure to avoid the major accidents	0.040	40%	100%	50%	10%	10%	100%	70%	80%
Rs3: Future budget for restoration	0.066	90%	80%	80%	80%	80%	80%	80%	70%
Rs4: Technology availability	0.018	60%	60%	60%	60%	60%	60%	60%	60%
Rd1: Adequacy of the flow capacity of the bypass pipeline	0.093	98%	85%	97%	100%	78%	89%	97%	96%
Rd2: Treatment capacity of sewage storage facility	0.022	90%	60%	0	0	0	0	0	0
$R = \sum w_i T_{mi}$	$\sum w_i = 1$	0.7509	0.7945	0.7015	0.7170	0.7590	0.7442	0.7414	0.7503

**Figure 5** | Quantified resilience index of eight small blocks' sewer networks.

The authors hope that the research on resilience in drainage areas of Seoul to cope with ground collapses can arouse more attention from the academic community on the application of the concept of resilience in the sewer network and seek out feasible ideas. However, this study has certain assumptions and limitations on the subdivision factors of resilience evaluation.

Due to the two complex sources of uncertainty and interdependence of various indicators related to SRI, there are still fundamental challenges to the comprehensive assessment of the resilience of the sewer network. Future studies are expected to replace them with more practical and easily available factors, and further optimize the resilience evaluation system. In addition, this study only considered the adverse effects of a single acute shock caused by ground collapse. Future studies can evaluate the resilience of sewer networks in the face of acute shocks such as earthquakes and floods.

ACKNOWLEDGEMENTS

This research was supported in part by the Chung-Ang University Young Scientist Scholarship in 2020 and in part by Korea Environment Industry & Technology Institute (KEITI) through project for developing innovative drinking water and wastewater technologies, funded by Korea Ministry of Environment (MOE) (2020002700015).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

- Almoghathawi, Y., Barker, K. & Albert, L. A. 2019 Resilience-driven restoration model for interdependent infrastructure networks. *Reliability Engineering & System Safety* **185**, 12–23.
- Alshehri, S. A., Rezgui, Y. & Li, H. 2015 Disaster community resilience assessment method: a consensus-based Delphi and AHP approach. *Natural Hazards* **78**, 395–416.
- Angkasuwansiri, T. & Sinha, S. K. 2015 Development of a robust wastewater pipe performance index. *Journal of Performance of Constructed Facilities* **29**, 04014042.
- Assad, A., Moselhi, O. & Zayed, T. 2019 A new metric for assessing resilience of water distribution networks. *Water* **11**, 1701.
- Attoh-Okine, N. O., Cooper, A. T. & Mensah, S. A. 2009 Formulation of resilience index of urban infrastructure using belief functions. *IEEE Systems Journal* **3**, 147–153.
- Bakhshipour, A. E., Dittmer, U., Haghighi, A. & Nowak, W. 2021 Toward sustainable urban drainage infrastructure planning: a combined multiobjective optimization and multicriteria decision-making platform. *Journal of Water Resources Planning and Management* **147**, 04021049.
- Binesh, N., Niksokhan, M. H., Sarang, A. & Rauch, W. 2019 Improving sustainability of urban drainage systems for climate change adaptation using best management practices: a case study of Tehran, Iran. *Hydrological Sciences Journal* **64**, 381–404.
- Bruneau, M., Chang, S., Eguchi, R., Lee, G., O'Rourke, T., Reinhorn, A., Shinozuka, M., Tierney, K., Wallace, W. & Winterfeldt, D. V. 2003 A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra* **19**, 733–752.
- Butler, D., Farmani, R., Fu, G., Ward, S., Diao, K. & Astaraie-Imani, M. 2014 A new approach to urban water management: safe and sure. *Procedia Engineering* **89**, 347–354.
- Casal-Campos, A., Sadr, S. M. K., Fu, G. & Butler, D. 2018 Reliable, resilient and sustainable urban drainage systems: an analysis of robustness under deep uncertainty. *Environmental Science & Technology* **52**, 9008–9021.
- Chang, S. E. & Shinozuka, M. 2004 Measuring improvements in the disaster resilience of communities. *Earthquake Spectra* **20**, 739–755.
- Chen, T., Yang, X., Chen, C., Deng, C., Wu, H. & Wu, J. 2020 Evaluation for the Resilience of Distribution Network. In: *2020 5th Asia Conference on Power and Electrical Engineering (ACPEE)*, pp. 2071–2076.
- Cheng, J. C. P. & Wang, M. 2018 Automated detection of sewer pipe defects in closed-circuit television images using deep learning techniques. *Automation in Construction* **95**, 155–171.
- Dong, X., Guo, H. & Zeng, S. 2017 Enhancing future resilience in urban drainage system: green versus grey infrastructure. *Water Research* **124**, 280–289.
- Guarino, P. M. & Nisio, S. 2012 Anthropogenic sinkholes in the territory of the city of Naples (Southern Italy). *Physics and Chemistry of the Earth, Parts A/B/C* **49**, 92–102.
- Haque, M. A., Teyou, G. K. D., Shetty, S. & Krishnappa, B. 2018 Cyber Resilience Framework for Industrial Control Systems: Concepts, Metrics, and Insights. In: *2018 IEEE International Conference on Intelligence and Security Informatics (ISI)*, pp. 25–30.
- Henry, D. & Emmanuel Ramirez-Marquez, J. 2012 Generic metrics and quantitative approaches for system resilience as a function of time. *Reliability Engineering & System Safety* **99**, 114–122.
- Hosseini, S., Barker, K. & Ramirez-Marquez, J. E. 2016 A review of definitions and measures of system resilience. *Reliability Engineering & System Safety* **145**, 47–61.
- Juan-García, P., Butler, D., Comas, J., Darch, G., Sweetapple, C., Thornton, A. & Corominas, L. 2017 Resilience theory incorporated into urban wastewater systems management. State of the art. *Water Research* **115**, 149–161.
- Kuliczowska, E. 2016a The interaction between road traffic safety and the condition of sewers laid under roads. *Transportation Research Part D: Transport and Environment* **48**, 203–213.

- Kuliczowska, E. 2016b [An analysis of road pavement collapses and traffic safety hazards resulting from leaky sewers](#). *The Baltic Journal of Road and Bridge Engineering* **11**, 251–258.
- Kwak, T. Y., Woo, S. I., Kim, J. & Chung, C.-K. 2019 [Model test assessment of the generation of underground cavities and ground cave-ins by damaged sewer pipes](#). *Soils and Foundations* **59**, 586–600.
- Maier, H. R., Lence, B. J., Tolson, B. A. & Foschi, R. O. 2001 [First-order reliability method for estimating reliability, vulnerability, and resilience](#). *Water Resources Research* **37**, 779–790.
- Mazumder, R. K., Salman, A. M., Li, Y. & Yu, X. 2021 [Asset management decision support model for water distribution systems: impact of water pipe failure on road and water networks](#). *Journal of Water Resources Planning and Management* **147**, 04021022.
- Ministry of Environment 2015 *Manual of Detailed Inspection of Sewer Pipelines in Response to Ground Subsidence (in Korean)*. Korea Ministry of Environment, Seoul, Republic of Korea.
- Ministry of Environment 2020 *Sewerage Statistics (in Korean)*. Korea Ministry of Environment, Seoul, Republic of Korea.
- Moradi, S., Zayed, T. & Golkhoo, F. 2019 [Review on computer aided sewer pipeline defect detection and condition assessment](#). *Infrastructures* **4**, 10.
- Moteff, J. 2005 Risk Management and Critical Infrastructure Protection: Assessing, Integrating, and Managing Threats, Vulnerabilities and Consequences, Congressional Research Service Report to Congress, Order Code RL32561.
- Mottahedi, A., Sereshki, F., Ataei, M., Nouri Qarahasanlou, A. & Barabadi, A. 2021 [The resilience of critical infrastructure systems: a systematic literature review](#). *Energies* **14**, 1571.
- Mugume, S. N., Diao, K., Astaraie-Imani, M., Fu, G., Farmani, R. & Butler, D. 2015a [Enhancing resilience in urban water systems for future cities](#). *Water Supply* **15**, 1343–1352.
- Mugume, S. N., Gomez, D. E., Fu, G., Farmani, R. & Butler, D. 2015b [A global analysis approach for investigating structural resilience in urban drainage systems](#). *Water Research* **81**, 15–26.
- Orencio, P. M. & Fujii, M. 2013 [A localized disaster-resilience index to assess coastal communities based on an analytic hierarchy process \(AHP\)](#). *International Journal of Disaster Risk Reduction* **3**, 62–75.
- Pandit, A. & Crittenden, J. 2016 [Index of network resilience for urban water distribution systems](#). *International Journal of Critical Infrastructures* **12**, 120–142.
- Patel, D. A., Lad, V. H., Chauhan, K. A. & Patel, K. A. 2020 [Development of bridge resilience index using multicriteria decision-making techniques](#). *Journal of Bridge Engineering* **25**, 04020090.
- Saaty, T. L. 1994 [How to make a decision: the analytic hierarchy process](#). *INFORMS Journal on Applied Analytics* **24**, 19–43.
- Saaty, T. L. 1999 Basic theory of the analytic hierarchy process: how to make a decision. *Revista de la Real Academia de Ciencias Exactas Fisicas y Naturales* **93**, 395–423.
- Saaty, T. L. 2008 [Decision making with the analytic hierarchy process](#). *International Journal of Services Sciences* **1**, 83–98.
- Seoul 2018 2030 *Master Plan on Sewerage Rehabilitation (in Korean)*.
- Shahata, K. F. 2013 *Decision-support Framework for Integrated Asset Management of Major Municipal Infrastructure*. Ph.D. thesis, Concordia University, Montréal, Canada.
- Tscheikner-Gratl, F., Sitzenfrei, R., Rauch, W. & Kleidorfer, M. 2016 [Integrated rehabilitation planning of urban infrastructure systems using a street section priority model](#). *Urban Water Journal* **13**, 28–40.
- Vugrin, E. & Camphouse, R. 2011 [Infrastructure resilience assessment through control design](#). *IJCIS* **7**, 243–260.
- WEF 2009 *Existing Sewer Evaluation and Rehabilitation: WEF Manual of Practice No. FD-6 ASCE/EWRI Manuals and Reports on Engineering Practice No. 62*, 3rd edn. McGraw-Hill Education, New York.
- WHO 2002 *Emergencies and Disasters in Water and Sewage Systems – Guidelines for Effective Response*. Pan American Health Organization (PAHO), Washington, DC.
- Wirahadikusumah, R., Abraham, D. M., Iseley, T. & Prasanth, R. K. 1998 [Assessment technologies for sewer system rehabilitation](#). *Automation in Construction* **7**, 259–270.
- Yang, M. D. & Su, T. C. 2008 [Automated diagnosis of sewer pipe defects based on machine learning approaches](#). *Expert Systems with Applications* **35**, 1327–1337.

First received 15 September 2021; accepted in revised form 10 November 2021. Available online 24 November 2021