

Zihai Shi, Masaaki Nakano, Yoshifumi Takahashi

**Structural Analysis and Renovation Design of Ageing Sewers  
Design Theories and Case Studies**



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# Preface

This book presents a systematic treatment of fracture-mechanics based structural analysis and renovation design of ageing sewers as semi-composite pipes. These have been employed for sewer renovation in Japan, especially in the Tokyo metropolitan area for more than fifteen years, with the total length of renovation construction now exceeding 700 km. The concept of a semi-composite pipe and the application of fracture mechanics of concrete in numerical modelling of the structural behaviour of a renovated sewer pipe are the two distinctive features of the established design theories that have emerged and matured with the development of a sewer renovation construction method (the SPR method, which received the top industrial technology development award in Japan, the Oukochi Memorial Prize 2013).

The general practice of sewer renovation in Japan, from site survey and structural design to renovation, is subject to the Japan Sewage Works Association's *Design and Construction Guidelines for Sewer Pipe Rehabilitation*. The Guidelines apply to two types of renovation method, namely, the independent (or stand-alone) pipe method and the composite pipe method, with the former being used mainly for non-man-entry sewers with circular cross section and the latter for both man-entry and non-man-entry sewers with arbitrary cross sections. In the composite pipe construction approach, a liner pipe is constructed inside an existing sewer by interlocking strips of surface materials made of polyvinyl chloride or polythene resin, and the annular space behind the liner is filled with cementitious grout under pressure to form a highly integrated structure. The Guidelines define a composite pipe as a composite structure requiring complete integration between the renovation layer and the existing pipe.

Test results show that the bond strength of cementitious grout is typically half the tensile strength of normal concrete. With this limited bond strength, the requirement for a rigid connection between the existing pipe and the renovation layer in the composite pipe method may not always be guaranteed. To fully explore the advantages of the composite pipe method in sewer renovation while keeping safe design in mind, a semi-composite pipe structure has been proposed based on three assumptions for the interface: a perfect bond after construction, a no-tension interface (i.e., the interface does not bear tensile force) and a perfect bond under compression. The resulting structure resembles a composite structure with mechanical connectors set in the compression zones along the interface that are intercepted by no-tension interface zones with free surfaces, and thus is called a semi-composite pipe structure.

The design approach for this semi-composite structure is based on the theory of limit state design. As a typical feature of this design approach, nonlinear structural analysis including crack analysis is performed on a semi-composite pipe under extreme load conditions to obtain its characteristic load-carrying capacity. The details of the renovation layer including the thickness and ratio of steel reinforcement are then determined using design formulas based on the ratio of member force to member strength with relevant safety factors considered. Next, a seismic performance

evaluation is carried out to ensure the renovated pipe meets the code requirements for earthquake resistance.

The leading authors of this book have been involved in designing the renovation of ageing sewers since the mid 1990s, and the design theories and design practices introduced here are the crystallisation of their collaborative research efforts, which have been greatly strengthened by their younger colleagues who have joined the team in the past five or six years. The book contains eight chapters. Chapter 1 introduces the background to sewer renovation in Japan, and Chapter 2 explains the composite pipe method. Chapter 3 introduces various fracture tests on renovated pipe specimens, and structural element and material property tests. Chapter 4 presents the basic theories of the fracture mechanics of concrete, and Chapter 5 develops the structural analysis theories of composite pipes as semi-composite structures, including an analysis on the local buckling of invert lining under groundwater pressure. Chapter 6 presents renovation design theories that include limit state design and seismic performance evaluation. The last two chapters focus on applications: Chapter 7 on the development of a design-aid programme, and Chapter 8 on design case studies.

The book was written as a reference work focusing on the latest technical developments in sewer renovation in Japan for both sewer engineers worldwide and students of civil and urban engineering. The authors are both researchers and practicing engineers with extensive experience in the renovation design of ageing sewers. Each chapter was written by one or two co-authors, and was edited for content, accuracy and style.

Just like an artist in painting or music, I sometimes feel that our daily engineering work such as the issues discussed in this book is as creative as the traditional arts that we enjoy for their beauty or emotional power. This may sound farfetched, but when you face a new project for which you are aware of only some of the mechanics principles required, you really need to rely on your engineering instinct, creative skill and imagination to identify the best approach. Our work may not be enjoyed for its beauty (normally you cannot even see the sewer), but its emotional power may be associated with the safe infrastructure of a modern society, of which a sewerage system is a vital component. If the readers of this book even partially agree with me, this will mean, at least for me, ‘mission accomplished’.

Z. Shi  
August 10, 2015

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# 1 Introduction

## 1.1 Recent Development in Sewer Renovation in Japan

In the modern world, a sewerage system increasingly serves as a vital lifeline that sustains the normal functioning of a society in which people live and work. Although sewers are normally out of sight (and thus “out of mind”, as a well-known sewer engineer once lamented), a malfunction of these underground facilities can have immediate effects on those who live in the affected areas. For instance, a road-cave-in accident as shown in Photo 1.1 due to the sudden collapse of an ageing sewer can sometimes cause loss of life, not to mention inconvenience for those living in the surrounding areas, as well as the monetary cost of repairs. The inadequate discharging capacity of a network of ageing sewers for surges of rain water in stormy weather can result in floor-level inundation of large areas, which not only disrupts the normal livelihood for many but also causes enormous damage to private property. Even relatively minor problems like clogged drains and emission of foul odours due to the dysfunction of ageing sewers in a small residential area can be distressing, especially when these ordeals are prolonged and repeated.



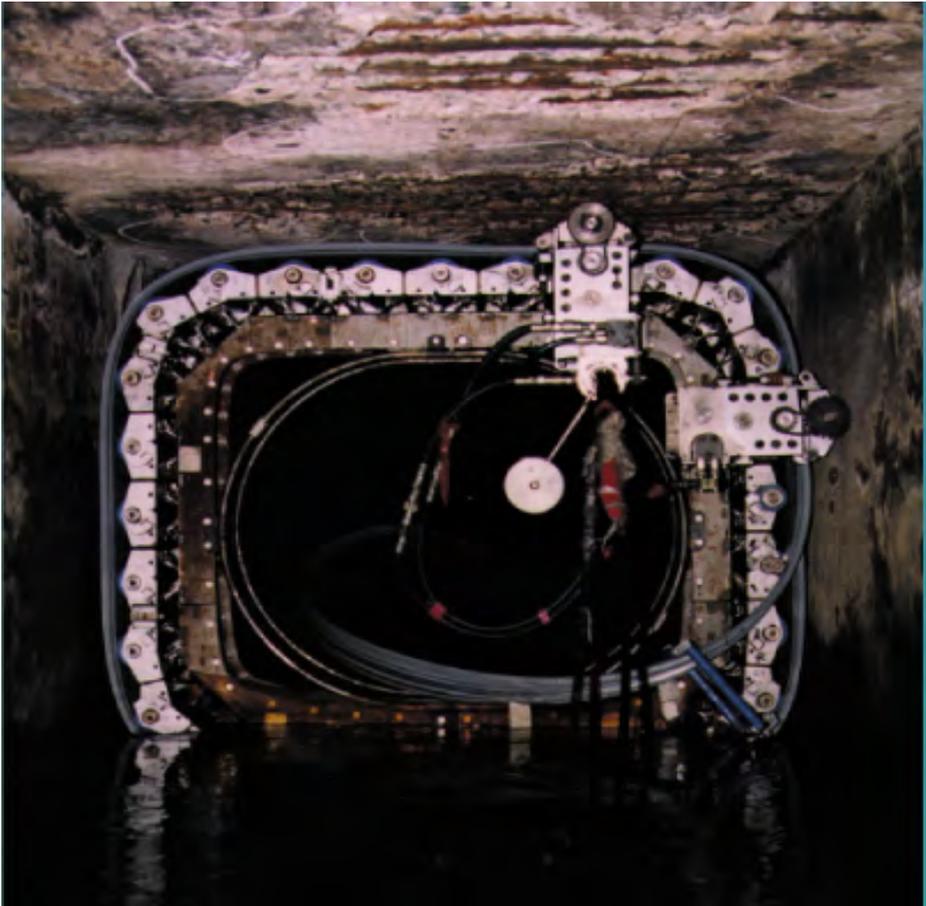
**Photo 1.1:** Road cave-in caused by the collapse of a sewer main (Tokyo)



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In general, as sewers approach and exceed their design service life of fifty years, the likelihood or frequency of malfunctions as discussed above increases, as a result of long-term material and structural deterioration caused by abrasion, chemical attack, excessive hydraulic flows, structural cracks and joint defects, and leaks and infiltration. Photo 1.2 shows an ageing sewer with the complete loss of cover concrete and severe corrosion of rebars in the reinforced concrete cover plate, which is a frequently-observed type of structural degradation in ageing sewers. Obviously, rehabilitation of these ageing sewers to ensure their safe operation and upgrade their functions is urgently needed and should be carried out systematically using modern renovation methods and design codes.



**Photo 1.2:** An ageing sewer with the complete loss of cover concrete and severe corrosion of rebars

In Japan, sewer rehabilitation began in 1987 by using the Sewerage Pipe Renewal (SPR) method. The principles of design and construction for sewer renovation are specified by the Japan Sewage Works Association's standard: *Design and Construction Guidelines for Sewer Pipe Rehabilitation* (JSWA, 2011). In this provisional code, renovation methods are classified into two categories: the so-called composite pipe method and the independent (or stand-alone) pipe method. The concept of the composite pipe method is to construct a composite structure by rigidly attaching a renovation layer, i.e., an inner lining to the existing pipe, and the renovated sewer is expected to bear the external loads using the combined resistance of the two structural components. On the other hand, in the independent pipe method a new pipe is constructed inside the existing one, ignoring the remaining strength of the ageing sewer. Note that the *Guidelines* were developed from a previous version, *Pipe Rehabilitation Handbook* (JSWA, 2001).

Since the late 1980s, the Sewerage Bureau of the Tokyo Metropolitan Government (TMG) has actively promoted the composite pipe renovation method in upgrading and reconstructing its ageing sewerage system (TMG, 2008). As a result, except when sewer replacement by open-cut construction is absolutely necessary, renovations of man-entry sewers with a wide range of cross-sectional shapes have been carried out using several certified composite pipe renovation techniques. The independent pipe method is sometimes used to renovate non-man-entry sewers with circular cross sections in the Tokyo area, but it is not used as frequently as the composite pipe method.

Photo 1.3 shows an ageing sewer during renovation construction using the SPR method, which is one of several composite pipe renovation techniques that have been approved by the Sewerage Bureau of the TMG to be employed in the metropolitan area at present. As seen, a liner-formation machine moves along the existing sewer with its pre-fabricated framework conforming to the cross-sectional shape of the sewer, creating an inner liner along the length of the existing sewer. The liner is formed by helically winding a continuous polyvinyl chloride (PVC) ribbed profile with interlocking edges. The annular space behind the liner is then filled with cementitious grout under pressure to form a highly integrated structure with the PVC liner bound to the existing sewer by grout after it has hardened naturally. For medium- to large-size man-entry sewers, the ribs of the profile are reinforced with steel to enhance the hoop strength and stiffness of the liner, and the structural strength of the renovated sewer is largely determined by the thickness and material characteristics of the renovation layer.

As seen, the ageing sewer after renovation in Photo 1.3 has been transformed into a compound structure composed of the existing sewer and the renovation layer of the reinforced liner and the grout, and is expected to function like a composite structure under external loads that include the surrounding earth pressure, groundwater pressure and the live load from traffic. Construction processes using similar renovation techniques may differ in detail from manufacturer to manufacturer. In one particular

method as shown in Photo 1.4, evenly-spaced steel frames are laid against the sewer's inner walls first, and then the liner is fabricated by fixing long PVC plates longitudinally to these preset frames, which is followed by grout injection.



**Photo 1.3:** An ageing sewer during renovation construction by using the SPR method

In order for the renovated sewer to resist external loads as a composite structure in which the continuity of stress or force flow through the interfaces is maintained, obviously the bond strength of grout to the ageing sewer has to be strong enough to endure large interface stresses that may arise under extreme load conditions. It is known that the bond strength of various types of high-strength mortar to concrete developed by several manufacturers in Japan has a wide range of variation, changing approximately from 1.5 MPa to 3.0 MPa. In general, the bond strength of cementitious grout is less than the tensile strength of normal concrete, and on average it is one half of the latter. With this limited bond strength, the requirement for rigid connection



**Photo 1.4:** A composite pipe renovation method by using evenly-spaced steel frames and long PVC plates to fabricate interlinings before grout injection

between the two different structural members in the composite pipe method may not always be guaranteed. Though the required bond strength could be achieved by pre-embedding sufficient mechanical connectors in the existing pipe to rigidly connect the two parts, employing such mechanical connectors in sewer renovation is unrealistic when considering a sewer's small cross section, its long length and the sheer cost of construction.

The leading authors of this book have been involved in designing the renovation of ageing sewers since the mid 1990s, and have developed a unique structural model for the composite pipe method in which a no-tension interface model is used to define an otherwise rigid connection between the contacting surfaces of the existing pipe and the renovation layer. In other words, the presumed rigid linkage between the two surfaces following renovation construction is severed when tension develops from the interfaces. The resulting structure is referred to as a *semi-composite pipe structure*, or, a *semi-composite pipe*. The design approach for this semi-composite pipe structure is based on the theory of limit state design. As a typical feature of this design approach, nonlinear structural analysis including crack analysis is performed on a semi-

composite pipe under extreme load conditions to obtain its characteristic load-carrying capacity. Details of the renovation layer including the thickness and ratio of steel reinforcement are then determined using design formulas based on the ratio of member force to member strength with relevant safety factors considered. Note that the member force is typically obtained by linear structural analysis under the design load condition, and the member strength is derived from the limit state of structural failure when the load-carrying capacity is obtained. In this book, a terminology of semi-composite pipe is coined to indicate the no-tension-interface structural model of a composite pipe. Therefore, when the term of composite pipe is used, it should be understood as such a structure.

One may question the wisdom of adopting such a seemingly complex numerical model and computational approach in the renovation design of ageing sewers: Why not choose a simpler approach using linear elastic analysis? The reason is that a good design in sewer renovation must be structurally safe and hydraulically functional. A simple but conservative model of the problem may require a thick interlining for the renovation that could greatly reduce the hydraulic capacity of the sewer. Such a design is unsuitable, even if it is structurally safe. Therefore, the purpose of employing a realistic structural model like the semi-composite pipe model in the current design approach is to obtain the minimum required thickness of the renovation layer, so that the renovated sewer is not only structurally safe but also functionally sound with its hydraulic capacity uncompromised by the renovation.

As this semi-composite structure concept and design methodology have been employed for sewer renovation in Japan, and especially in the Tokyo metropolitan area for more than fifteen years, with a total construction length exceeding 700 km, this book summarises the design theories and practices as a reference book for both sewer engineers worldwide and students of civil and urban engineering. The book contains eight chapters. Chapter 1 introduces the background to sewer renovation in Japan, and Chapter 2 explains the composite pipe renovation method. Chapter 3 introduces various capacity tests of renovated sewer pipes and structural element and material property tests. Chapter 4 presents the basic theories of fracture mechanics of concrete, and Chapter 5 develops structural analysis theories of composite pipes as semi-composite structures, including an analysis on the local buckling of invert lining. Chapter 6 presents renovation design theories that include limit state design and seismic performance evaluation. The last two chapters focus on applications with Chapter 7 on the development of a design-aid programme, and Chapter 8 on design case studies. The authors are researchers and practicing engineers with extensive experience in the renovation design of ageing sewers. Each chapter was written by one or two co-authors, and was edited by Zihai Shi for content, accuracy and style.

## 1.2 Past Sewer Projects and Emerging Challenges

In 1884, in the wake of a cholera outbreak, sewer construction was started in the Kanda area in Tokyo as the first project of its kind in Japan. The sewer system thus constructed is the Kanda Sewer System, the first modern sewer system in Japan (Photo 1.5).



**Photo 1.5:** Kanda sewer system (still in service)

For financial reasons, however, the construction had to be discontinued after a two-kilometre-long sewer system was completed. In 1894, Osaka began transforming its open-channel, masonry sewerage system into culverts, with necessary reinforcement and modifications. During the decade from 1887 to 1897, sewer plans for other major cities such as Nagoya, Fukuoka, Hiroshima and Kobe were drawn up, and the construction of sewerage systems gradually began. As so, sewerage construction in Japan in the major cities began.

In the subsequent years, the functions and purposes of sewer systems were expanded to include improvement of the living environment, flood control, and water contamination prevention. Thus, sewerage systems became widely recognised throughout the country as part of urban infrastructure. As a result, the percentage of

sewered population in Japan has reached 97% in the ordinance-designated cities. The percentage in other cities, however, remains about 64%, and the national average is 73% (as of 2008).

As these figures indicate, the task for sewerage projects in non-ordinance-designated cities is to raise the percentage of the sewered population. In the ordinance-designated cities, where sewerage projects began early, it is to rehabilitate and functionally upgrade the ageing facilities. This section outlines the sewerage projects that have been carried out thus far in Tokyo and explains the challenges to be addressed and the measures being taken.

### 1.2.1 Modern sewerage projects

In the 1880s, there was an outbreak of cholera in Tokyo. The number of patients exceeded 750,000, and more than 260,000 died. The main cause was thought to be the urban structure, particularly the drinking water supply and sewerage systems in those days, and there were increasing calls for sewer construction to prevent cholera. In response to this public demand, the Kanda Sewer System, which was a pioneering sewerage project in modern Japan, was constructed in 1884 and 1885 prior to the construction of drinking water supply systems. Its construction, however, was halted two years later after just two kilometres of sewers had been completed. This was partly because the necessity and benefits of sewerage systems were not widely recognised. The direct reason was the lack of public funding because the use of government subsidies was not permitted.

One reason why the Kanda Sewer System project was discontinued was the Government's poor understanding of its importance, as well as the fact that the project was not being carried out systematically as part of urban reform. In addition, the construction technology was immature, and it was difficult to procure construction materials. Also, releasing untreated sewage into rivers was a problem.

After the project was stopped, in 1890 the Government decided to give priority to constructing drinking water supply systems; construction began in 1892, and water supply commenced in some areas in 1898. Later, the construction of sewerage systems resumed, and in 1908 the Tokyo City Sewer Design, which formed the basis of sewerage plans for the present-day Tokyo, was adopted.

The plan called for the construction of combined sewerage systems, which meant that sewers and sewage treatment facilities were to be constructed in an integrated manner. Under the plan, sewer construction began in 1913 in Ryusenji in Shitaya Ward, and construction of the Mikawajima Sewage Treatment Plant began in 1914. Figure 1.1 shows the length of sewers constructed each year and how the unit sewage volume, which is the basis for sewerage planning, and the storm-water runoff coefficient have changed over the years in Tokyo.

As shown, the sewerage systems constructed in Tokyo can be classified, according to quality and quantity, into two groups: those constructed during the pre-war period

and those constructed from 1955. The sewerage systems constructed during the pre-war period have small unit sewage volumes and storm-water runoff coefficients. The total length of those sewers, which were constructed to serve the former Tokyo City area, is about 1,950 km. Most of the sewerage systems constructed from 1955 were built rapidly from around 1960, when Tokyo was selected as the host of the 1964 Olympic Games. From the mid-1960s to 1994, when the percentage of sewered population reached 100%, sewers were constructed at a rate of about 400 km/year. During that period, the unit sewage volume increased by a factor of 4 and the storm-water runoff coefficient by a factor of about 1.5 compared with the pre-war levels. These trends in sewer construction reflect changing lifestyles and urbanisation.

### 1.2.2 Emerging challenges related to urban sewerage

#### 1.2.2.1 Functional degradation

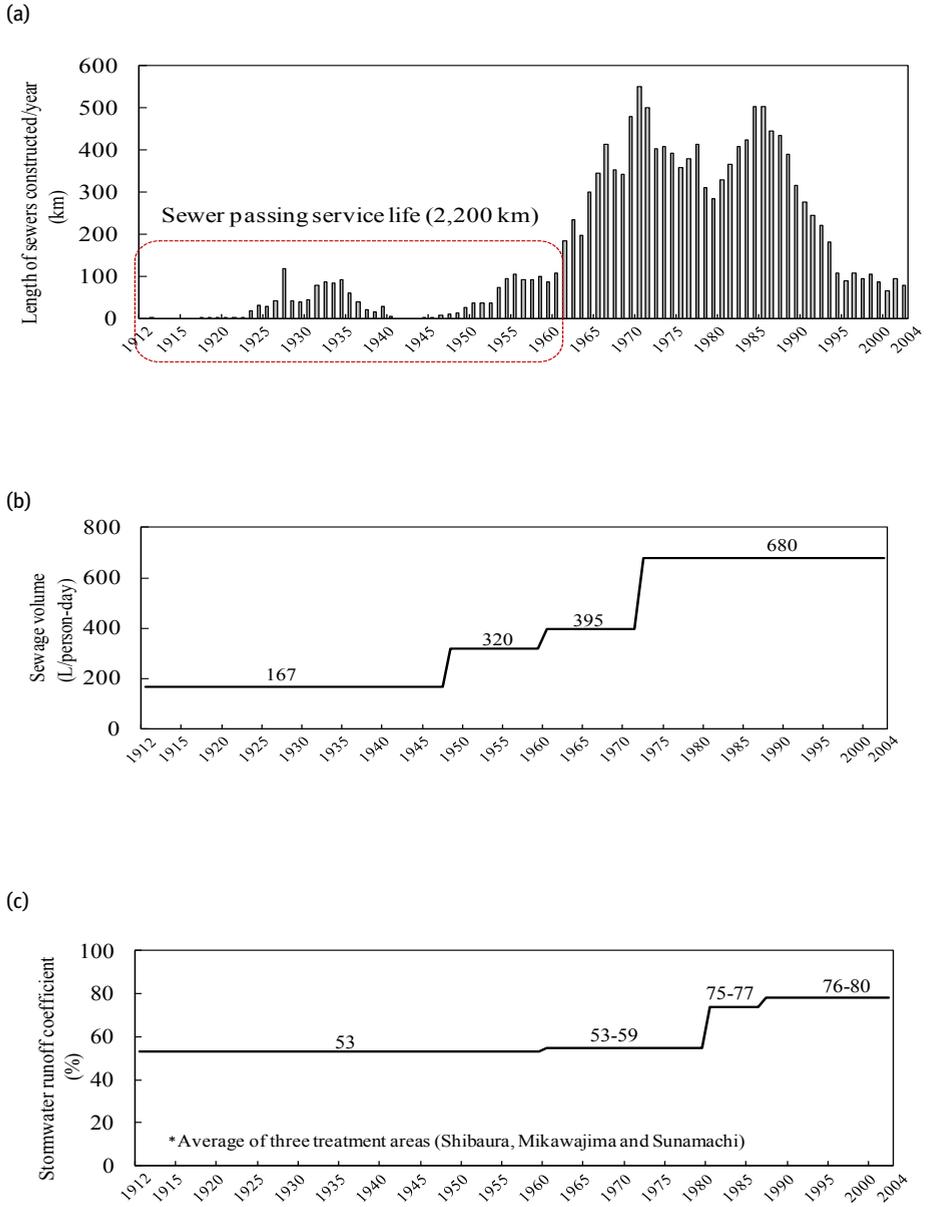
Changes in the volume of incoming sewage directly affect the drainage capacity of sewers. As shown in Fig. 1.1, storm-water runoff increased with the progress of urbanisation, and the drainage capacity of most of the sewers constructed during the pre-war years and up to around 1980 is smaller than that of the later sewers by about 40% (the runoff coefficient increased from 53–59% to 75–80%). This factor has contributed to the aggravation of flood damage in recent years. Table 1.1 shows the number of flooded houses in Tokyo from 1989 to 2000. As shown, many houses were flooded in those years (4,136 houses in 1989, 2,907 in 1991, 5,719 in 1993, 3,542 in 1999) although such flooding was caused by frequent localised heavy rains.

Sewage volume has also increased. The volume of sewage released into sewers per person per day has quadrupled from 167 to 680 litres, and population has also increased. To cope with the situation, various storm-water control measures have been taken to enlarge and strengthen infrastructure facilities such as augmenting sewer mains, increasing pump stations, increasing pump drainage capacity and the capacity of treatment plants, and projects for improving combined sewer systems have also been carried out. It has not been possible, however, to replace all old sewers mainly because of financial constraints.

**Table 1.1:** Number of stormwater-flooded houses in central Tokyo and frequency of heavy rains

Year	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Number of flooded houses	4,136	508	2,907	13	5,719	515	94	65	233	163	3,542	619
Number of more- than-50-mm rainfall events*	2	2	0	0	4	4	1	0	1	2	4	6

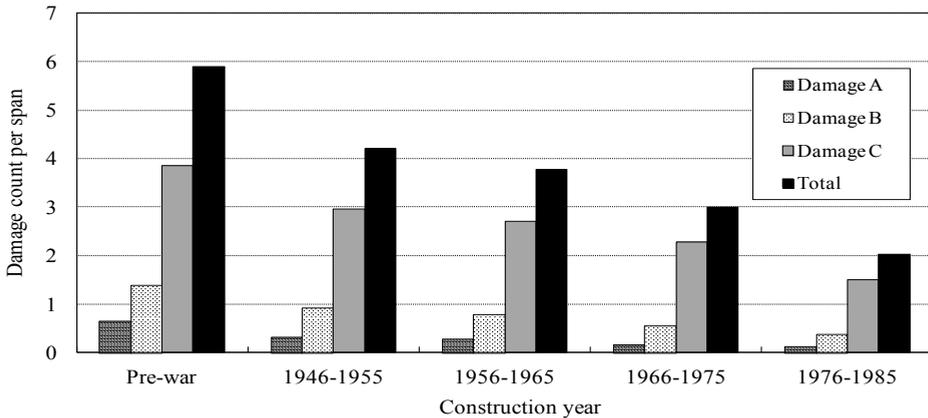
\* The design rainfall adopted by the Tokyo Metropolitan Government is 50 mm/hr.



**Figure 1.1:** Variations of sewer length, volume and runoff coefficient with time in central Tokyo: (a) the length of sewers constructed; (b) sewage volume; and (c) stormwater runoff coefficient

### 1.2.2.2 Structural degradation

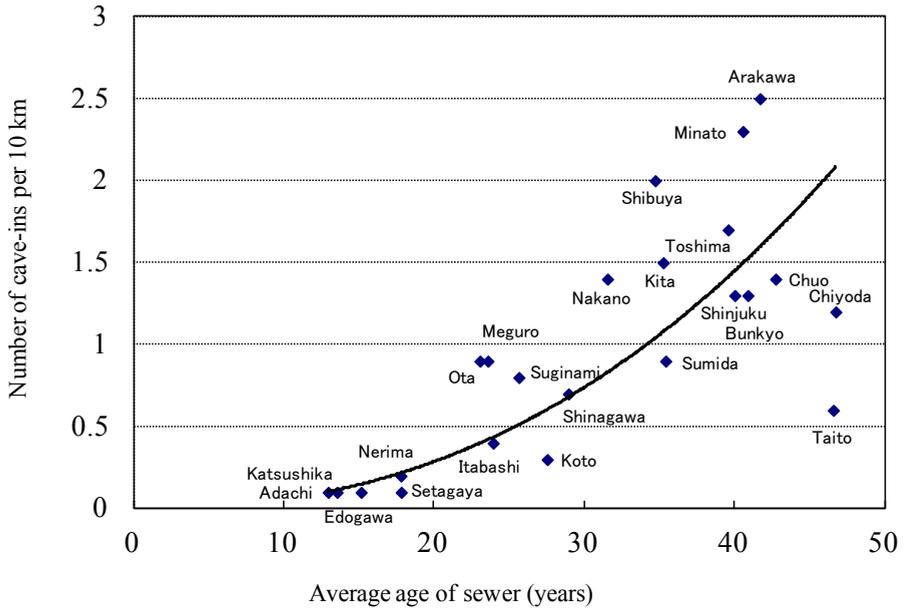
The sewer environment is corrosive and degrading, and sewers can also be adversely affected by increasing traffic load and land subsidence. Therefore, phenomena such as breakage of sewer pipes and disconnection of a branch pipe from a sewer main can occur, allowing sediment to flow into the sewer with groundwater and cause the road to cave in. Figure 1.2 shows the damage counts per span of sewers constructed during different periods. Needless to say, old sewers tend to show more damage than new sewers.



Note: 1) About 20% of total length was surveyed; 1 span ≈ 30 m.  
 2) Damage refers to sewer breakage, cracking or joint displacement.  
 3) Damage counts are calculated based on survey results of 1993.

Figure 1.2: Damage counts per span in central Tokyo

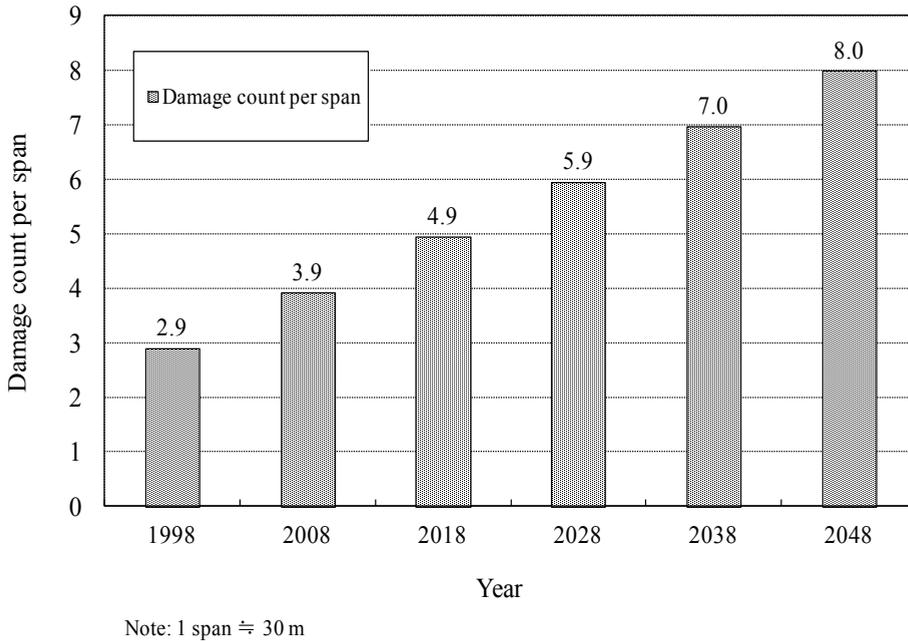
Figure 1.3 shows the relationship between the number of road cave-ins (per 10 km) caused by sewer damage in Tokyo and the average age (the number of years elapsed after construction) of sewers based on 1998 data. As is evident from the figure, there are differences in the number of cave-in incidents between the wards where sewers were constructed in recent years such as Adachi, Edogawa, Katsushika and Setagaya and those where sewers were constructed earlier such as Chuo, Bunkyo, Minato and Toshima. In wards located on the soft soil layers of the Yurakucho formation, some of which have suffered regional land subsidence, such as Arakawa, Sumida and Kita, the number of road cave-ins tends to be large relative to the average age of sewers. These data clearly indicate that degradation in structural strength is correlated with not only age-related factors but also other factors such as ground conditions and past regional land subsidence events.



**Figure 1.3:** Number of road cave-ins and average age of sewers in central Tokyo

On the basis of the sewer damage and road cave-in data shown above, an attempt has been made to predict the future situation of the sewers, assuming the current level of maintenance. Figure 1.4 shows predicted sewer damage counts based on the data shown in Fig. 1.2, obtained by taking into consideration possible future increases in the length of old and deteriorating sewers. For the purpose of calculation, it is assumed that in the 23 wards of Tokyo, a single sewer span is 30 m. As seen, the predicted damage count per span was 2.9 in 1998, and it will increase by a factor of 1.7 in 2018, and by a factor of 2.4 in 2038. Thus, the number of damage sites is likely to increase as the total length of old sewers increases.

Similarly, the occurrence of road cave-ins in the coming years can be estimated from the fact that the average number of cave-in incidents per year in the 10 years up to 1998 was 1,600. The number of cave-ins is expected to increase by a factor of 2.3 in 20 years and by a factor of 5.2 in 40 years. These grim predictions clearly indicate the importance of taking measures to prevent the ageing of sewerage systems, also from the viewpoint of maintaining road traffic and normal urban functions.

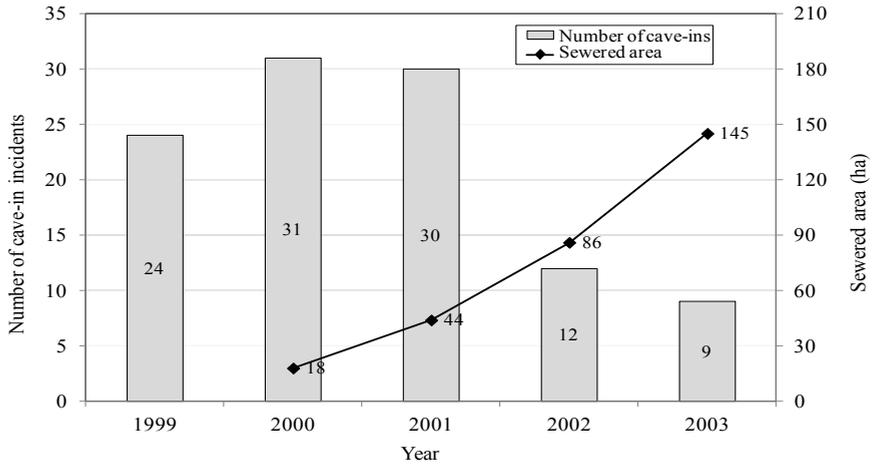


**Figure 1.4:** Predicted damage counts per span (average in central Tokyo, 1998)

### 1.2.3 Necessity of reconstruction projects

In order to cope with the problems mentioned above, the TMG has been working since 1994 to switch from merely responding to the symptoms, to a preventive maintenance approach by not only replacing or repairing parts of old sewers but also carrying out reconstruction projects to increase capacity as well as rehabilitate its ageing facilities. Note that reconstruction projects imply the construction of new sewers and the rehabilitation of ageing sewers, with the latter including sewer renovation and repair.

Figure 1.5 shows the number of road cave-in incidents in a designated region (273 ha) covered by the priority plan (a plan specifying the priorities of areas and measures drawn up to accelerate the effects of reconstruction projects adopted in 2003) and the coverage of sewer reconstruction between 1999 and 2003 (PFIJ, 2012). As shown, the number of road cave-in incidents has decreased with the progress of reconstruction projects, demonstrating the effectiveness of the projects.



**Figure 1.5:** Relationship between the number of road cave-in incidents and the coverage area of reconstructed sewerage systems (TMG, 2008)

### 1.3 Sewer Renovation in Reconstruction Projects

The use of sewer renovation methods is indispensable in urban sewer reconstruction projects. Today, there are various methods with a growing track record. This section explains why sewer renovation is necessary in reconstruction projects, and shows the classification of renovation methods and their track records in Japan. Also, the basic methodology for selecting a renovation method by the Sewerage Bureau of the TMG to be used in its sewer reconstruction projects is discussed.

#### 1.3.1 Background: Why rehabilitation?

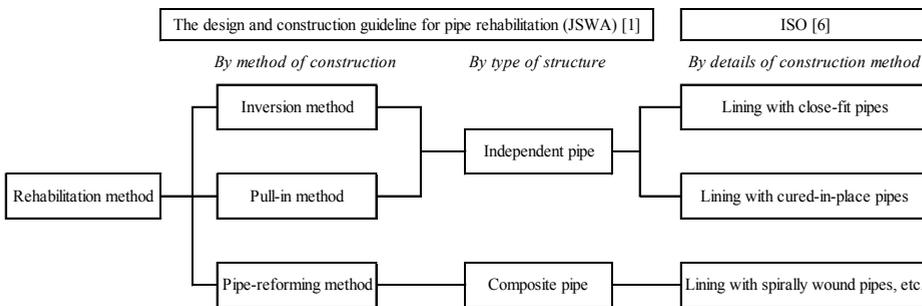
In order to renew or reconstruct ageing sewers and meet the required functionality and durability, it had been common practice to dig out old sewer pipes and install new ones by the cut-and-cover method. In urban areas, however, the underground space is increasingly crowded with many utility pipes and buried structures, and it is also necessary to carry out sewer reconstruction economically without affecting road traffic and the surrounding environment as much as possible.

This is why various sewer renovation methods have been developed. A common feature of these methods is that construction materials and equipment can be brought in through existing manholes and, without removing the existing pipe, renovation construction can be carried out from inside the existing structure by manufacturing

strong inner linings that are rigidly attached to the walls of the ageing sewer and greatly strengthen it.

### 1.3.2 Classification of renovation methods and their track records

Figure 1.6 shows the classification of pipe renovation methods based on the *Guidelines* and ISO standards (JSWA, 2011; ISO, 1986). The *Guidelines* deal with investigation, design and construction management related to sewer renovation methods. The *Guidelines* classify renovation methods according to the method of construction and the structural type after renovation. The former classification corresponds to pipe-forming methods, and the latter corresponds to design methods. The *Guidelines* include tables that classify renovation methods based on the type of material and the type of pipe-forming method, and introduces 23 independent pipe methods and 5 composite pipe methods.



**Figure 1.6:** Classification of pipe renovation methods

As of 2011, the total length of sewers rehabilitated by renovation methods in Japan was 5,617 km (PFIJ, 2012), and the total length of renovation construction per year has been on the increase. Even so, the length of sewers rehabilitated thus far accounts for only 1.4% of the total sewer length of 400,000 km. Hence, it is obvious that rehabilitation of ageing sewers will continue to be the major category of sewerage projects for a long time. The renovation methods classified by the method of construction as described in the *Guidelines* are explained below.

1. **Inversion method:** A liner pipe is formed by inserting a cylindrical liner made of a base material (glass fibre, organic fibre, etc.) impregnated with thermosetting resin into an existing pipe by the inversion method, then the resin is hardened by applying hot water, steam or other heat source while keeping the liner in close contact with the inner surface of the existing pipe by applying air or water pressure from inside the liner.

2. Pull-in method: A liner pipe is formed by softening and deforming a thermoplastic resin (polyvinyl chloride or high-density polyethylene) pipe and inserting it into an existing pipe by the pull-in method. The new pipe is then left to expand while still hot and then cool down and harden, with the liner kept in close contact with the inner surface of the existing pipe by applying air or water pressure from inside the liner. Also, a liner pipe can be formed by the pull-in method by following the same construction procedure as the inversion method, except for changing the method of construction from inversion to pull-in.
3. Pipe-reforming method: In this method, a renovated pipe is constructed by forming interlinings along the length of the existing pipe by interlocking strips of surface materials (polyvinyl chloride, polyethylene, etc.) and grouting the annular gap between the lining and the existing pipe with cementitious material to achieve structural integrity of the composite pipe thus formed. As explained in Section 1.1, due to the limited bond strength of the cementitious grout, such a composite pipe as defined by the *Guidelines* is structurally treated as a semi-composite pipe in this book. There are several pipe-reforming methods in Japan, which mainly differ in how the interlining is produced. The three widely-used methods for lining fabrication are the profile winding interlocking, the assembled panel interlocking and the liner segment interlocking method.

According to the *Guidelines*, pipe structures after renovation can be classified into two types: an independent pipe and a composite pipe, as defined below.

1. Independent pipe: A pipe that is strong enough to act as an independent structure and that has the same or higher load-carrying capacity and durability as a newly installed pipe
2. Composite pipe: A composite structure that consists of an old pipe and a renovation layer rigidly bonded together as a single integrated structure, and that has the same or higher load-carrying capacity and durability as a newly installed pipe

The classification into independent pipe and composite pipe categories is reflected in their respective design methods. The main difference is that while the former does not take the existence of the old pipe into consideration, the latter treats not only the liner but also the old pipe as its structural members. The design theory for an independent pipe is based on the flexible pipe assumption and is used for the inversion method and the pull-in method, and the design theory for a semi-composite pipe as discussed in this book is applied to the pipe-reforming method. This semi-composite pipe concept and the corresponding design theory are unique to Japan and were first adopted by the Sewerage Bureau of the TMG in its sewer reconstruction projects.

### 1.3.3 Tokyo's approach to reconstruction

Of the total length of sewer pipes of about 15,000 km (as of the end of 2011) in central Tokyo, the length of those exceeding the design service life of 50 years is approximately 2,200 km (about 14%). As exemplified by the Kanda Sewer System which is still in service 120 years after its construction, some of the ageing sewers in this category are still functional. Therefore, the TMG has drawn up a policy of extending the service life of those still in sound condition as much as possible. To improve the entire sewer network, priority in selecting ageing sewers for reconstruction is determined by considering the degree of deterioration, drainage capacity, construction conditions and cost. Criteria for actions to be taken according to the degree of pipe damage are as follows:

1. Pipe without damage: To be kept in service
2. Pipe with minor damage: To be renovated and kept in service
3. Pipe with major damage: To be replaced

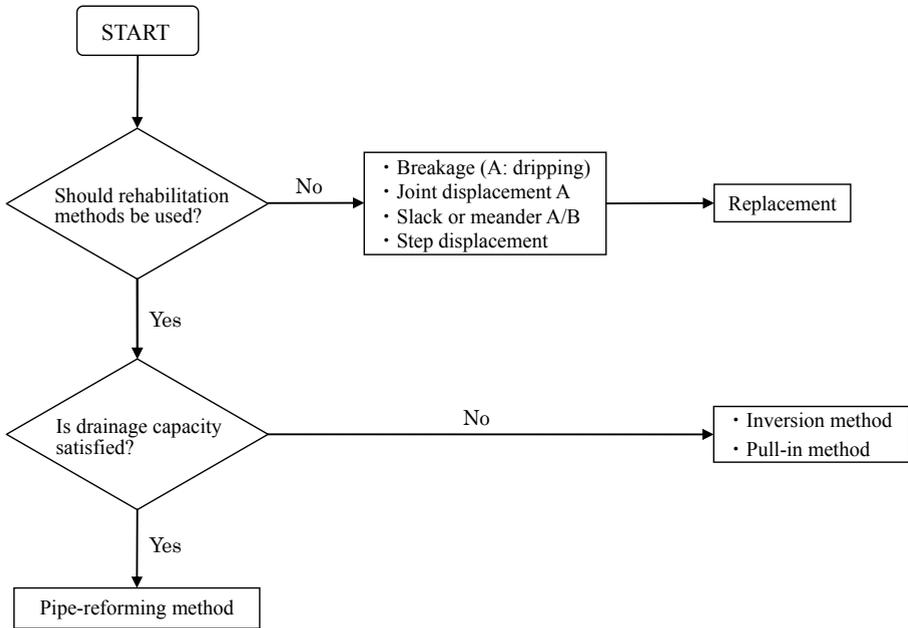
The existing pipe is checked as follows (the survey method is described in detail in Chapter 2): in the case of a man-entry pipe with a diameter of 800 mm or more, the degree of soundness of the pipe is evaluated through visual inspection and laboratory tests on sample specimens taken from the site; in the case of a non-man-entry pipe with a diameter of less than 800 mm (80% of all sewer pipes fall into this category), a self-propelled video camera is used to inspect the pipe.

Before rehabilitation methods were developed, it was standard practice to use the cut-and-cover method for reconstruction projects even when damage was minor. Today, the sewer rehabilitation approach is adopted in many projects in order to reduce the influence on road traffic and local residents. In general, the cost of no-dig sewer rehabilitation is only half that of cut-and-cover construction. Another advantage of no-dig rehabilitation is that its environmental impact is small because construction by-products from excavation are not generated. No-dig sewer rehabilitation, therefore, is essential for reconstruction projects.

The TMG approves the use of a no-dig pipe rehabilitation method in the metropolitan area according to criteria such as design conditions, strength and performance requirements, and verification test methods. So far, three pipe-reforming methods and eight inversion or pull-in methods have been approved.

Figure 1.7 shows Tokyo's methodology for selecting a pipe rehabilitation method. As shown, the kinds of damage to which the no-dig rehabilitation method cannot be applied are "breakage (A: chipping)," "joint displacement A," "slack or meander A/B," and "step displacement" shown in Table 1.2. In principle, the pipe-reforming method is to be used in other cases. If the required drainage capacity cannot be obtained when the pipe-reforming method is used for a small-diameter pipe, the independent pipe method, which employs thinner liners, is to be used. As discussed

in Section 2.2 of Chapter 2, the composite pipe method is superior to the independent pipe method in terms of reliability and economy.



**Figure 1.7:** Flowchart illustrating Tokyo's approach for selecting methods for sewer reconstruction

Table 1.2: Soundness evaluation criteria for video-camera-based and eyeball investigation (Tokyo)

Item	Damage level		
	A	B	C
Pipe breakage	Reinforced concrete pipe	Longitudinal crack with a width of 2 mm or more	Longitudinal crack with a width of less than 2 mm
	Earthenware pipe	Longitudinal crack with a length of less than 1/2 of pipe length	
Pipe cracking	Reinforced concrete pipe	Circumferential crack with a width of 2 mm or more	Circumferential crack with a width of less than 2 mm
	Earthenware pipe	Circumferential crack with a length of less than 2/3 of circumference	
Pipe joint displacement		Earthenware pipe: 50 mm or more	Earthenware pipe: less than 50 mm
		Reinforced concrete pipe: 70 mm or more	Reinforced concrete pipe: less than 70 mm
Pipe corrosion	Reinforcing bar exposure	Aggregate exposure	Roughened surface
Slack or meander of pipe		Equal to or greater than 1/2 of inside diameter	Smaller than 1/2 of inside diameter
		Gushing	Seeping
Water intrusion		Equal to or greater than 1/2 of inside diameter of lateral pipe	Smaller than 1/10 of inside diameter of lateral pipe
		1/2 or more of inside diameter blocked	
Lard deposition or tree root intrusion			

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Yoshifumi Takahashi

## 2 The Composite Pipe Construction Method

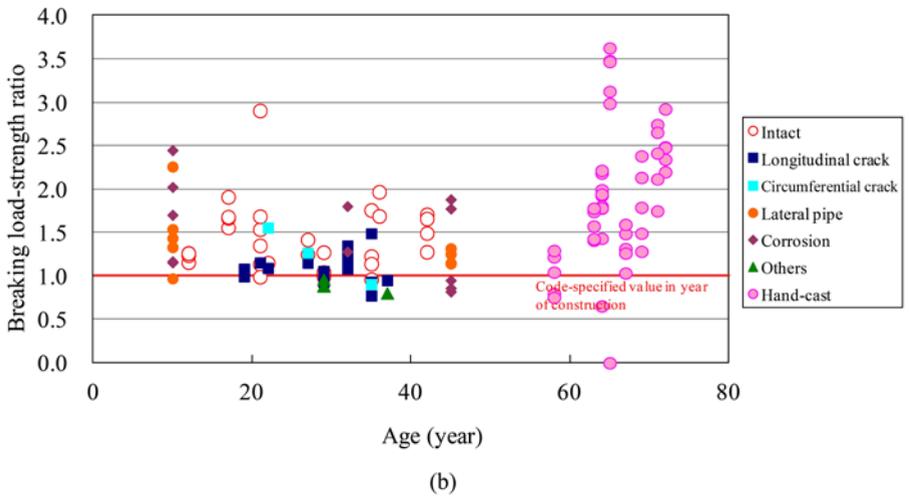
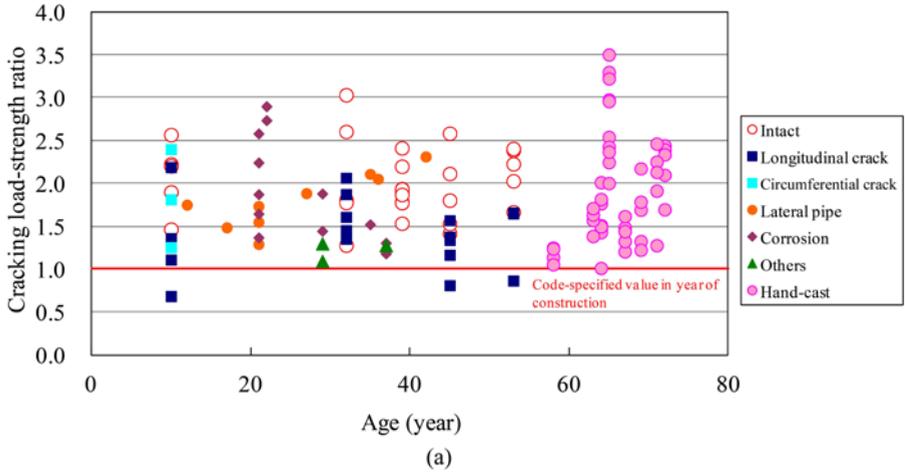
### 2.1 What Is a Composite Pipe?

The term “composite pipe” was first coined in the *Pipe Rehabilitation Handbook* published by the Japan Sewage Works Association in 2001 (JSWA, 2001). Based on its definition, the existing sewer and the renovation layer in a composite pipe are designed to resist external loads as an integrated structure, and the load-carrying capacity and durability are required to be comparable or superior to a newly-constructed sewer. In order for the existing pipe to function like a permanent member, concrete strength needs to be retained for about 50 years after completion of rehabilitation work.

To evaluate the strength of old concrete pipes in preparation for reconstruction projects, the Tokyo Metropolitan Government (TMG) dug up a total of 130 ageing pipes from 26 sewer lines over a period of two years from 1999 to 2000. A series of tests including the JIS external pressure test, uniaxial compression test and carbonation depth test were carried out on specimens taken from the dug-up pipes. Figure 2.1 shows the relationships of the cracking and fracture loads of each pipe divided by the code-specified value at the time of construction and the age of the pipe. Data points for the 60-year-old or older pipes indicate the hand-cast reinforced concrete pipes buried in the pre-war years, and those for the less-than-60-year-old pipes indicate the centrifugally-cast reinforced concrete pipes (Hume pipes: HP) buried in the post-war years. As shown, there is no clear correlation between age and strength ratio, and even if pipe deterioration occurs during a period of 70 years of service, the strength of installed pipes still satisfies the code requirements.

Figure 2.2 shows the relationship between the uniaxial compressive strength and the age of HP specimens by type of damage. As shown, the strength of buried concrete does not decrease for about 40 years. A comparison between damaged pipes and undamaged pipes reveals no significant difference in average strength, indicating that the damage was not caused by pipe deterioration.

From these test results, it can be concluded that because the initial strength of buried concrete pipes is retained even in cases of chemically induced deterioration, the concept of the composite pipe for sewer renovation is valid.



**Figure 2.1:** Relationship between the strength of dug-up pipes and the age: (a) cracking load; and (b) fracture load

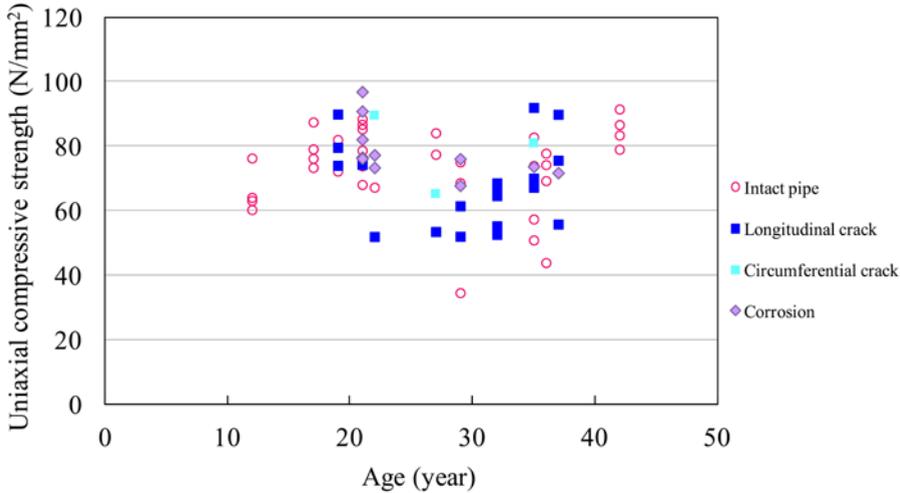
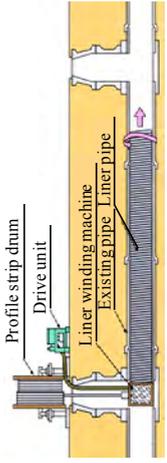
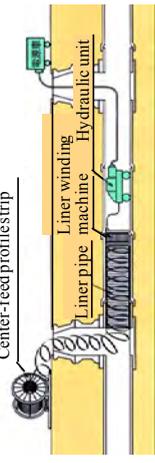
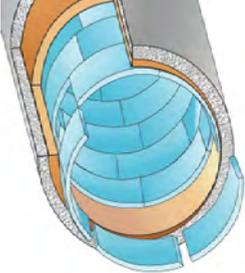


Figure 2.2: Uniaxial compressive strength of dug-up Hume pipes versus pipe age

## 2.2 Classification of Pipe-Reforming Methods

In Japan, five pipe-reforming methods for sewer renovation have been developed and employed in sewer reconstruction projects. These methods are summarised in Table 2.1. In all the methods, materials and equipment can be brought in through a manhole 60 cm in diameter, the existing pipe can be renovated by the trenchless method, and the gap between the liner pipe and the existing pipe is grouted with mortar so as to achieve structural integrity. In the SPR method and the Danby method, a PVC profile strip is spirally deployed by a winding machine to form a liner pipe. In the 3S segment method, the PALTEM Flow-Ring method and the PFL method, plastic and high-density polyethylene pipe materials are manually assembled in the existing pipe. These five methods can be used to form not only circular pipes but also pipes with a rectangular or horseshoe-shaped cross section. Among them, the SPR method, the Danby method and the PALTEM Flow-Ring method allow the interlining to be fabricated while keeping the sewer in service.

Table 2.1: Pipe-reforming methods (JIWET, 2009a–c, 2011, 2012a)

Method	SPR Method	3S Segment Method
Method illustration	Jacking type	
	<p data-bbox="577 1252 598 1408">Travelling type</p> 	
Description	<p data-bbox="790 862 873 1421">A PVC profile pipeline is formed in the existing pipe, and the annular gap between the existing pipe and the profile liner is grouted to form a strong composite pipe.</p> <p data-bbox="880 862 963 1421">(1) Circular pipe: Pipes smaller than 2,200 mm in diameter are constructed by the jacking method, and pipes 800–4,750 mm in diameter are constructed by the travelling winder method.</p> <p data-bbox="971 862 1053 1421">(2) Non-circular pipe: Pipes with a shorter side length of 800 mm or more and a longer side length of 6,000 mm or less are constructed by the travelling winder method.</p>	<p data-bbox="790 171 937 784">Transparent and lightweight plastic liner segments are manually brought into the existing pipe and assembled with nuts and bolts. Then, the gap between the liner and the existing pipe is filled with 3S grout to ensure structural integrity of the composite pipe thus formed.</p>

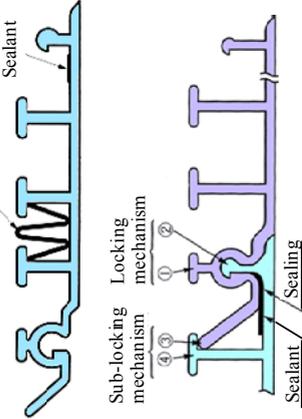
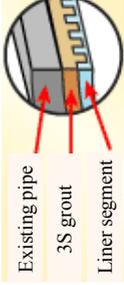
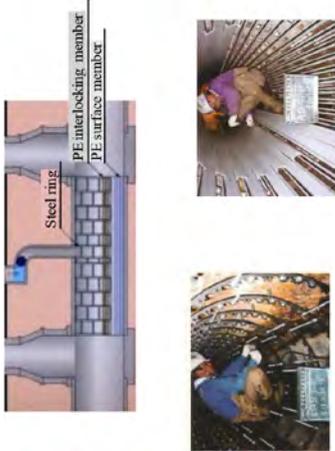
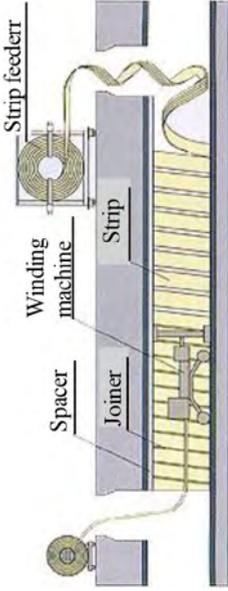
Lining method	Winding a profile strip and inserting a wound liner	Manually bringing in and assembling segments
Materials	Steel reinforcement (W-shaped, for #80 SW)	
		
Main materials	PVC (profile strip), mortar	Plastic segments, 3S grout
Applicable diameter range (mm)	250–4,750 mm dia., non-circular pipe: shorter side 800 mm or more, longer side 6,000 mm or less	1,000–4,000 mm dia., non-circular pipe 1,000–5,000 mm on side
Characteristics	<ul style="list-style-type: none"> <li>• Constructibility: The jacking method and the traveling winder method can be used. Applicable to various pipes such as non-circular cross section pipes and sharply curved (5D) pipes. Slope adjustments can be made according to pipe diameter.</li> <li>• Quantity: 18–460 m (pipe fabrication only)</li> <li>• Sewer service during rehabilitation: Possible (water depth 60cm)</li> <li>• Work area: The equipment and work area required are small (length: 25 m, number of vehicles: 3).</li> </ul>	<ul style="list-style-type: none"> <li>• Constructibility: There is no need for large equipment for bringing in liner segments through a manhole. The degree of completeness of grouting can be visually observed easily. Versatility is high so as to meet diverse construction needs such as curved pipe construction and concurrent liner construction in two directions.</li> <li>• Quantity: Circular pipe (800 mm dia.): about 6.5 m/day (typical) Non-circular pipe (2,200 × 2,200 mm): about 3.1 m/day (typical)</li> <li>• Sewer service during rehabilitation: Not possible</li> <li>• Work area: Small work area (length: 25 m, number of vehicles: 3)</li> </ul>
Trade association	Japan SPR Method Association	3SICP Technology Association
Date of certification	May, 1993	March, 2004

Table 2.1: Pipe-reforming methods (JIWET, 2009a–c, 2011, 2012a) (Continued)

Method	PALTEM Flow-Ring Method	Danby Method
Method illustration		
Description	<p>Steel rings brought into the existing pipe through a manhole are assembled with bolts, and interlocking members and surface members are installed to the steel rings. Then, the gap between the existing pipe and the surface members is grouted with high-fluidity high-strength mortar to form a composite pipe.</p>	<p>A PVC strip is pulled into the existing pipe, wound spirally and joined together by using a winding machine to form a continuous spiral-wound pipe. Then, the gap between the existing pipe and the spiral-wound pipe is grouted.</p>
Lining method	<p>Manually bringing in and assembling steel rings</p>	<p>Manually bringing in and winding a strip</p>
Materials	