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MANUAL 5

Rehabilitation of water mains and storage tanks: technologies and decision support tools

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1 Introduction

1.1 Scope

The scope of the current TRUST manual is the identification and organisation of best-practice maintenance and rehabilitation techniques of water mains and storage tanks at the operational level.

This manual presents a service-oriented portfolio of rehabilitation techniques, based upon a thorough assessment of the existing and emerging offers in water supply systems. It presents as well Life-Cycle Costing (LCC) and Life-Cycle Assessment (LCA) as decision tools for defining sustainable rehabilitation and repair strategies.

This is the fifth volume of a series of manuals developed in scope of the TRUST project (www.trust-i.net). The other volumes include the global framework of infrastructure asset management (Manual 1), specific guidelines for policy-making at a national or regional level (Manual 2) and for strategic and tactical planning at the utility level (Manuals 3 and 4) as well as a portfolio of rehabilitation techniques in drainage systems (Manual 6).

1.2 Document structure

The document has four chapters, being the first the present introductory chapter.

Chapter 2 focuses on the rehabilitation technologies for water mains, including the classification of the technologies, the non-structural and structural renovation techniques, the replacement techniques and a methodology for selecting the most adequate technique.

Chapter 3 explains the rehabilitation technologies used for renovating storage tanks and describe several types of interventions typically carried in these assets (e.g., coating solutions, epoxy solutions)

Chapter 4 presents LCA and LCC as decision tools for defining sustainable rehabilitation and repair strategies.

1.3 Target public

This manual is targeted for water professionals (Cabrera *et al.*, 2011):

TARGET GROUP	PROFILE	NEEDS AND EXPECTATIONS
Water professionals: Technical staff	Control all the technical aspects of urban water systems other than management Technical formation to be expected Close profile to the scientific community	Expect technical content with details for practical uses Particularly technical documents; no research details necessary

2 Rehabilitation technologies for water mains

2.1 Introduction

Many technologies and application methods for the rehabilitation of water pipes are well documented in existing standards (e.g., BS EN 12889: 2000, BS EN 15885: 2010; EN ISO 11295: 2008) and in other references of the area (e.g., Simicevic and Sterling 2001, Stein 2001, NRC 2003, Heijn and Larsen 2004). A classification of the main technologies used in pipes is proposed in the current document based on these references and on emerging technologies.

The main procedures carried out in rehabilitation works are described as well as the solutions used for structural and non-structural renovation and for open-trench and trenchless pipe replacement. Despite the rehabilitation technique being case-dependent, guidelines for the selection of the most adequate techniques are presented in terms of the main key-drivers for the pipe rehabilitation, namely the type of anomalies – structural, hydraulics, water quality or operation and maintenance (O&M).

2.2 Classification of pipe rehabilitation technologies

The rehabilitation techniques in water supply and distribution pipes can be divided into two main categories: **renovation** and **replacement** techniques.

- **Renovation** is a work that incorporates all or part of the original fabric of the pipe by means of which its performance is improved (ISO/DIS 11295: 2008).
- **Replacement** is a rehabilitation of an existing pipe system by the installation of a new pipeline system, without incorporating the original fabric (ISO/DIS 11295: 2008).

There are other classifications like the one used in wastewater systems which considers the **repair** techniques as a third group of rehabilitation techniques (EN 15885: 2013; Stein 2001). However, in this document, the interventions associated to corrective repairs of a set of structural anomalies (e.g., joint repair) are considered as renovation techniques.

- **Repair** is rectification of a local damage (ISO/DIS 11295: 2008).

A repair is typically an action that allows temporary operating conditions, at localized site, until a more permanent rehabilitation or replacement is carried out.

There are also other infrastructure interventions which improve the system performance and extend the useful life of the pipe systems (e.g. pipe cathode protection) that are not included in this report as these are considered a **maintenance** procedure.

- **Maintenance** is keeping an existing pipe system operational without the installation of additional fabric (ISO/DIS 11295: 2008).

The **renovation techniques** can be divided into two groups:

- **non-structural techniques**, if they do not guarantee total or partial pipe structural resistance (e.g. single repair of a joint or internal pipe coating);
- **structural techniques**, if they guarantee total or partial pipe structural resistance (e.g. pipe lining). To have a long term vision of the service.

The **replacement techniques** are also divided in two groups:

- **open trench techniques** (e.g. conventional method or non-conventional narrow trench method);
- **trenchless techniques** (e.g. pipe bursting, pipe reaming, pipe eating).

The classification of rehabilitation techniques in water supply and distribution pipes is summarized as follows.

This classification is in agreement to the one used for wastewater and storm water systems (Volume 6 of the series of TRUST manual) and is based on the Portuguese, European and International standards such as EN 15885: 2010 and ISO/DIS 11295:2008 for renovation techniques; NP EN 12889: 2000 and EN 1610:2008 for replacement techniques. Besides this standards there other specific standards with design concepts and principles (i.e. EN 752:2008, EN 14801:2006, EN 13689:2002) and specific product standards (i.e. EN 13566-1:2002, EN 1916:2002) that are applied.

Classification of rehabilitation techniques in water pipes

TYPE OF INTERVENTION		FAMILY OF TECHNIQUES	TECHNIQUE
Renovation	Non-structural	Repair	Internal joint seals
		Coating or spray-lining	Use of cementitious mortars, concrete or polymeric resins
	Structural	Conventional sliplining	Lining with continuous pipes or sliplining Lining with discrete pipes
		Modified sliplining	Close-fit pipe lining - Fold and form - Rolldown, drawdown, swagelining
			Cured in-place pipe lining - Inverted in-place installation - Winched in-place installation
Replacement	Open trench	Conventional	Conventional open trench
		Non-conventional	Narrow trench Mole plough
	Trenchless	Steerable techniques	Pipe bursting Pipe implosion or pipe crushing Pipe ejection, pipe extraction or pipe pulling Pipe ejection with pilot pipe
		Non-steerable techniques	Pipe eating or modified micro-tunnelling Pilot jacking with pipe bore Pipe reaming or directional drilling

2.3 Non-structural renovation technologies

2.3.1 Brief overview

The **non-structural renovation techniques** consist of the reparation of a localized set of anomalies (e.g. joints or short pipe sections) or of the relining of existing pipes. These techniques are applied to repair small leaks, to control internal corrosion and to solve localized water quality problems. However, they do not guarantee the pipe integrity, neither pipe structural resistance.

The non-structural renovation techniques described herein are:

- internal joint seals;
- coating or spray-lining.

Due the continuous development of processes and possible application variants, only the most used techniques are presented. In the next sections, the referred techniques are described including a summary of the main characteristics, application conditions, advantages/disadvantages and the corresponding reference standards.

2.3.2 Internal joint seals

In water supply systems, pipe repair includes single interventions of corrective repairs for a set of physical anomalies in pipe systems. Repair techniques are widely used in wastewater systems; however, in water supply systems, only the internal joint seals and internal pipe sealing are used.

This technique has two methods of application:

- synthetic rubber joint seal;
- epoxy resin and glass or carbon fibre joint seal.

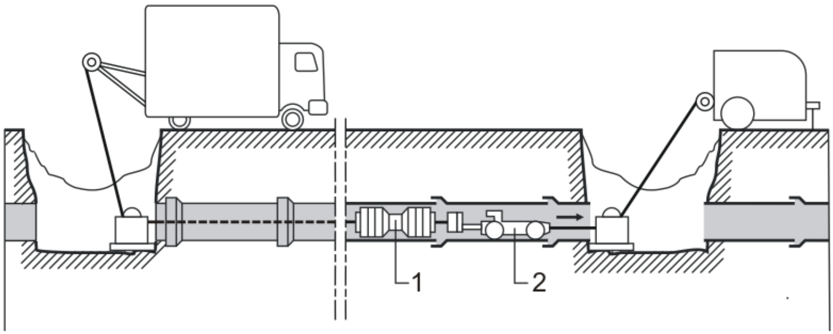
The repair with **synthetic rubber joint** consists of filling the empty spaces by injecting mortar cement or a flexible material followed by the application of a synthetic EPDM (ethylene-propylene-diene) cylindrical rubber. This application can be made manually in accessible pipes or through a robot inserted in non-accessible pipes.

This method when applied to defective joints requires that the joint inner surface as well the inner pipes walls are clean and smooth. After that, the joint can be filled from inside the pipe with cement mortar or filled with flexible material (this material is used to absorb joint displacements). The joint inner surface should be aligned with the inner surface of the pipes. This surface must be cleaned again and coated with lubricant to facilitate rubber adherence. Afterwards, the application of the EPDM rubber and of the stainless steel bands can be carried out. Finally, a device that compresses the stainless steel band over the rubber is applied, ensuring that it is does not move during the curing process (NRC 2003).

Internal joint/pipe seals can be applied to pipe diameters ranging from 250 to 6000 mm and to different pipe materials, such as steel, cast iron, reinforced concrete, asbestos cement, PolyVinyl Chloride (PVC) and High/Medium Density PolyEthelene (HDPE/MDPE). For small pipe diameters, between 250-500 mm, this technique needs to be applied with a robot simultaneously with CCTV inspections.

The **advantage** of this method is that allows restoring the water supply service immediately after finishing the repair works. Also, it adapts very well to joint deformation in soils with differential settlements.

After cleaning the repair surface, the in-situ epoxy resin and glass or carbon fibre seal application method consist of filling the joint or the fissure with polystyrene (filling foam) followed by an application of a flexible mastic seal to regularize the surface. Afterward, the joint is painted with an epoxy resin to ensure adherence and, then, a glass or carbon fibre fabric is applied. Finally, the joint should be painted with filling and polishing epoxy resin several times. This procedure can take up to two or three days, due the cure of the materials. During this period, the water supply service must be suspended.



Legend: 1 – Repair equipment; 2 – CCTV

However, this solution when applied in quantity is more economical. It should also be preferably applied to large diameters (accessible) otherwise a robot and CCTV are required to apply it.

The main features and conditions of application of joint repairs are summarized as follows:

FEATURES	MAIN CHARACTERISTICS	
Relevant standards	EN 15885:2010	
Materials	Cement mortar and EPDM rubber (Method I) Polystyrene, flexible mastic, epoxy resin, glass or carbon fibre fabric (Method II)	
Installation methods	Method A: synthetic rubber joint seal Method B: in-situ epoxy resin and glass or carbon fibre seal In both cases, the installation for small diameters is assisted through mechanical means and CCTV inspections.	
Geometric characteristics	Diameter range	250 – 500 mm (mechanical means and CCTV) 500 – 600 mm (manual)
	Maximum length Execution of bends	Variable -
Performance	- Does not affect the hydraulic capacity of the pipe ☺ - Does not assure pipe structural integrity ☹	
Installation characteristics	- The necessary surface for work execution is minimal ☺ - The access to the existent pipe requires excavation at one end of the pipe ☹ - Requires prior cleaning of the inner surface of pipe in the repair area ☹ - Requires simultaneous CCTV inspection for small diameters ☹ - The success of the technique depends on the material adherence to the joint surface ☹ - Need to suspend the water supply service and to implement temporary lateral service connections ☹ - Does not interfere with the lateral service connections ☺ - Low cost solution (Method A) ☺ or high cost solution (Method B) ☹	

Legend: ☺ Main advantages; ☹ Main disadvantages.

2.3.3 Coating or spray-lining

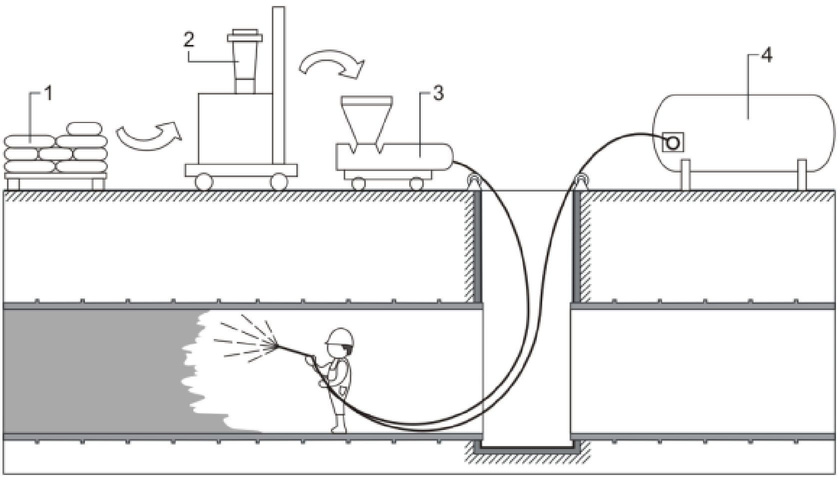
The renovation technique of coating or spray-lining consists of applying cementitious mortars, concrete or polymeric resins on the pipe inner surface. The material may be reinforced with steel or glass fibres (EN 15885: 2010).

The **cement mortar spray-lining** was quite used in the past, tending to be in disuse nowadays due to the long cement mortar curing time. I was typically used in metallic pipes with a high internal corrosion and has two protective actions: passive and active. The passive protective action results from physical isolation of the metallic pipe-wall avoiding the progress of corrosion. The active protective action results from a highly alkaline environment of the mortar which has an inhibitory effect on iron oxidation. The layer thickness depends on the pipe diameter and material, usually varying between 3 and 102 mm. The technique can be applied to water supply pipes with diameters ranging from 150 to 1500 mm.

The **coating with polymeric resin** is a highly competitive economic alternative for small pipe diameters (up to 300 mm), though it can also be used for higher diameters. Two polymeric resins can be used: epoxy and polyurethane. The **epoxy resin** was much used in the last decade but is currently in disuse due to its quite long curing time. This resin has been replaced by the **polyurethane resin**, which has a much faster cure and is a more reliable coating. The resins should be certified to be applied in water supply and distribution pipes differing only on the hardening technology. The polymeric lining has the advantage of being smoother than the cement mortar, resulting in a pipe with higher hydraulic capacity.

The **inner coating application** requires that the internal pipe-wall must be completely cleaned, polished and dried. Valves installed in the pipe should be disassembled prior to the coating application or, alternatively, they should be cleaned after the application.

The coating can be applied in a mechanical way (usually triggered by a winch or by a robot) or manually depending on the extension or the diameter of the pipe to be rehabilitated. It is often placed using rotary mechanical devices like diffuse jet (spray) inserted in a hose end spreading the material over the inner pipe surface (Figure 3.2). The process should be assisted by the simultaneous CCTV inspections in order to monitor the progression and execution quality and also to identify the location of singularities, such as valves, bends and service connections.



Legend: 1 – Coating material; 2 – Mixing equipment;
3 – Dosing pump; 4 – Compressor.

Once the process of installing the coating is ready, the pipe ends are buffered and it follows the curing process which takes 12 to 24 hours for cement mortar, 16 hours for epoxy resin and 2-3 hours for polyurethane resins. Thereafter, the pipe should be cleaned with pressurized water and disinfected before placing it back into service.

The coating or spray-lining is a **non-structural and temporary solution** often driven by water quality problems, though these problem have been much overcome with the use of more resistant resins, like the polyurethane resin. This technique has lower costs than the lining techniques. Additionally, it allows to increase the pipe hydraulic capacity (resulting from a smooth inner surface of the pipe and from the increase of the non-rehabilitated pipe useful cross section) and it can accommodate bends up to 45º (depending on pipe diameter); however, the technique requires the interruption of the water supply service during the execution process.

In the last decade, these solutions were widely used in metallic pipes (i.e. steel or cast iron) for rehabilitation driven by water quality problems resulting from internal corrosion. Nowadays, this technique is in less use, since it does not assure neither structural integrity nor structural resistance for the rehabilitated pipe and have a limited duration. This is a temporary solution that involves some investment.

The main features and conditions of application are summarized as follows:

FEATURES	MAIN CHARACTERISTICS	
Relevant standard	EN 15885:2010	
Materials used	Cement mortar, concrete, polymeric resin	
Installation methods	Method A: mechanical application; Method B: manual application	
Geometric characteristics	Diameter range	Minimum: 200 mm (mechanical application) 1600 mm (manual application) Maximum: 600 mm (mechanical application) limitless (manual application)
	Maximum length	100 m (mechanical application) Limitless (manual application)
	Execution of bends	Allows to build bends up to 45°
Performance	- Increases hydraulic capacity of the pipe ☺ - Does not assure pipe structural integrity ☹	
Installation characteristics	- The necessary surface for work execution is minimal ☺ - Access to the existing pipe requires excavation at one end ☹ - Requires prior cleaning of the inner surface in the repair area ☹ - Depends of the coating adherence to the pipe inner surface ☹ - Needs to suspend the water supply service and to implement temporary service connections ☹ - Does not interfere with the lateral service connections ☺ - Temporary solution ☹	

Legend: ☺ Main advantages; ☹ Main disadvantages.

2.4 Structural renovation technologies

2.4.1 Brief overview

The structural renovation techniques of pipes consist of inserting a new resistant and sealed tube in the host pipe without opening a trench. These techniques are the only ones that ensure full, or partial, structural resistance and integrity of the existing pipe. The main lining techniques for water supply and distribution pipes are:

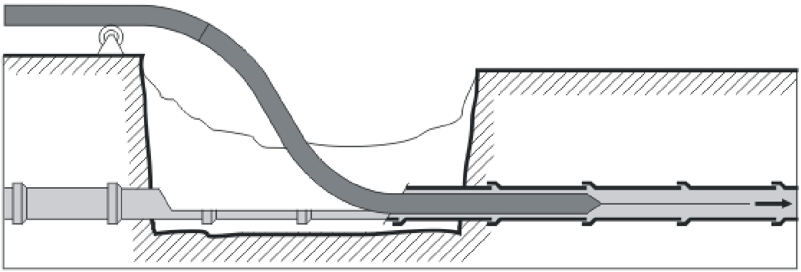
- lining with continuous pipe or sliplining ;
- lining with discrete pipe;
- close-fit pipe lining;
- cured-in-place pipe lining;
- lining with adhesive-backed hoses.

The first two techniques are **conventional sliplining** techniques, whereas the last three are **modified techniques.**

In the following sections each of these techniques is described and the main characteristics, advantages, disadvantages and corresponding standards are presented. A classification of the structural resistance for the inserted pipe is also described.

2.4.2 Lining with continuous pipe or sliplining

The lining with continuous pipe or sliplining is a conventional sliplining technology. It consists of inserting a continuous flexible tube into the existing pipe. The inserted tubes can be pipes trenches welded on-site or a continuous pipe provided in coil, depending on the diameter. The lining is made with a smaller diameter being the cross section dimensions not changed after its installation.



This lining process involves opening two access points (entry pits) at the pipe ends, typically at direction changes or at singularities. For the application of the technique the pipe section to be renovated must be out of service and free of valves and fittings (e.g. bends, valves).

Before the lining process, the inner pipe walls should be cleaned and polished. The lining process starts with the connection of a cable with a pulling head into the pipe.

This cable is then stretched by a hydraulic jack that drags the lining to the interior of the existing pipe until it is totally inserted

The external pipe walls should be properly protected and lubricated to prevent damages

If the inserted pipe is shorter than the existing one another pipe needs to be welded to increase its length. The welding process should be properly monitored in agreement to the quality control procedures.

Usually, the annular space between pipes is filled with a mortar or a resin that affixes the new pipe. This prevents water entering and allows a better distribution of the external loads avoiding an eventual collapse of the existing pipe. Prior to this, it is necessary to identify, locate and isolate the lateral service connections to prevent the entrance and obstruction with the filling material.

The main features, conditions of application, advantages and disadvantages of the lining with continuous pipe, according to ISO/DIS 11295:2008 e EN 15885: 2013, are:

FEATURES	MAIN CHARACTERISTICS	
Relevant standards	- EN 13566-1:2002, EN 13566-2:2005, ISO 11296-1:2009, ISO 11296-2, EN 15885:2010 (wastewater) - EN 14409-1:2004, ISO 11298-1:2010, ISO/DIS 11298-2:2008 (water supply) - ISO/DIS 11295:2008 (general)	
Materials	PE, PE-X, PP	
Installation methods	Insertion performed by pull or push through entry pits located at the pipe ends	
Geometric characteristics	Diameter range	100 - 2000 mm
	Maximum length	300 m
	Execution of bends	Bends with large radius can be accommodated
Performance	- Significant reduction in hydraulic capacity due cross section reduction despite the reduction of the roughness ☹ - Assures pipe structural integrity ☺	
Installation characteristics	- Need to insert continuous pipe (welded connection) ☹ - Can be applied to most types of pipes ☺ - Rapid installation ☺ - Required surface working space: • Minimum for small pipe diameter (< 100 mm), supplied in coils ☺ • High for larger pipe diameter, pipe storage and work execution ☹ - Access to the existing pipe requires digging at pipe insertion points ☹ - Need to interrupt the supply. ☹ -Need to fill empty space between new and existing pipes with resin/mortar. ☹ - Reconnection of laterals generally requires excavation ☹	

Legend: ☺ Main advantages; ☹ Main disadvantages.

The **main advantage** of this technique is **providing structural resistance** equal or higher than the one from the existing pipe, since a new pipe is inserted. It is a relatively simple and rapid technique to apply, allowing the execution of bends with high radius of curvature. Different types of thermoplastic materials may be used, being the HDPE the most widely used with pressure classes equal or higher than the existing pipe.

The **main disadvantage** is the loss of hydraulic capacity of the new pipe in comparison with the existing one, due to the significant reduction of the pipe diameter (between 30 and 60%) (prEN 15885:2008). However, the new pipe has a smoother wall than the existing one, which can partially compensate the diameter decrease; in case, the existing pipe having a high incrustation level, removed during the cleaning process, the hydraulic capacity of the pipe can even increase. The analysis of the hydraulic capacity of the pipe should be assessed before and after the application of this technique, being a technique particularly adequate for large diameter pipes (Heijn e Larsen, 2004).

Another disadvantage of this technique is the difficulty in overcoming small curvature bends and installed fittings that cannot be removed. In general, most valves, tee-junctions and bends should be removed prior to the lining process, and installed afterwards. These fittings cannot be reinstalled in the new pipe as this has a different diameter, and new ones have to be installed. Also the installation of the service connections requires local excavation.

The welding process is one of the weaknesses of this technique, as it should be adequately executed by trained staff and monitored according to the quality procedures.

2.4.3 Lining with discrete pipes

The lining with discrete pipe is similar to the previous technique of lining with continuous pipe. This technique uses short pipe sections which are assembled to the existing pipes by fitting or by welding (depending of the joint type) to form a continuous pipe. A sliplined pipe substantially reduces the cross-sectional area of the existing pipe (ISO 11295: 2008, EN 15885: 2013). However, the reduction in the friction factor of the lined pipe compared to the previous, old unlined pipe could significantly compensate for the reduced internal diameter. This technique is mainly used in wastewater and stormwater sewers (NRC, 2003).

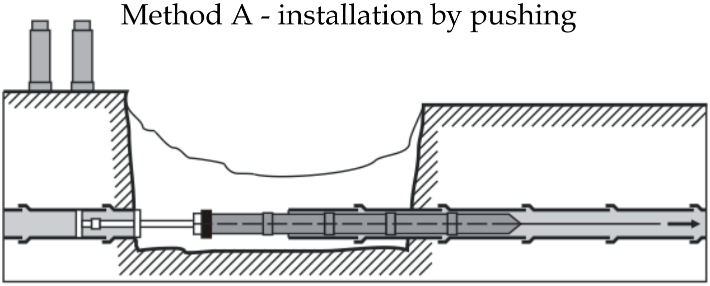
The installation of discrete pipes can be carried out by different methods:

- Method A: **installation by pushing**

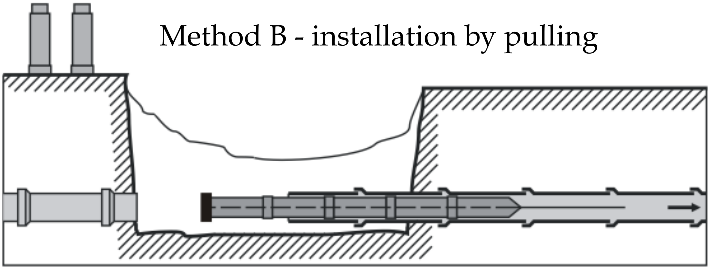
  The pipe sections are assembled at an entry pit according to joint type (by welding or fitting) being the partial displacement equal to the pipe section length.
- Method B: **installation by pulling**

  In this method, the first section is connected to a pulling head which pulls the sections being then assembled at the entry pit. The partial displacement is equal a pipe section length.
- Method C: **individual pipe placement at the final position.**

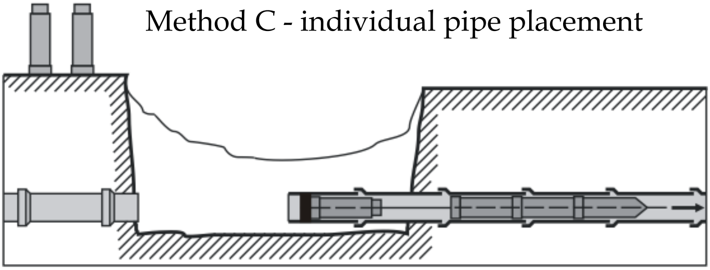
Method A - installation by pushing



Method B - installation by pulling



Method C - individual pipe placement



The installation of pipes requires the excavation of entry pits at the pipe ends. Inserted pipes are of smaller diameter than the existing ones. Thus, after installation, the annular space between the new and the existing pipes needs to be grouted and the grouting pressure must not exceed the buckling resistance of the liner. Grouting the annular space allows liner affixation, avoids water entry and circulation, allows uniform loads along the pipe and helps to prevent pipe collapse.

Additionally, it is necessary to locate and to buffer the lateral service connections to prevent the entry of filling material. For application of this technique the host pipe needs to be out of service and free of obstructions or water.

This technique may be simpler, faster and more economic technique than the slip-lining for rehabilitation of short lengths of pipe and of small diameters. It requires less working space at the surface of the job site which is limited to the entry pits. The main disadvantages are the loss of hydraulic capacity and the difficulty to execute bends (which may require local excavation).

The **main advantage** of this technique is the reinforcement of the structural resistance of the existing pipe. Other advantages are the fast insertion and the possibility to accommodate bends with large radius (WRc, 2001).

The **main drawback** is the significant reduction of the hydraulic capacity of the pipe due to the cross section reduction not compensated by the roughness decrease. When installation methods A and B are used, bends can generally not be accommodated. Other disadvantages include the possibility to occur fluctuations during grouting, the need of trained staff for welding the pipe joints and the reconnection of lateral service connections generally requires excavation.

The main features, conditions of application, advantages and disadvantages of the lining with discrete pipe technique are presented as follows:

<table>
<tr><th>FEATURES</th><th colspan="2">MAIN CHARACTERISTICS</th></tr>
<tr><td>Relevant standards</td><td colspan="2">- EN 13566-1:2002, ISO/DIS 11295: 2008, ISO 11296-1: 2009, EN 15885:2010 (wastewater)
- EN 14409-1:2004, ISO 11298-1:2010, ISO/DIS 11298-2:2008 (water supply)
- ISO/DIS 11295:2008 (general)</td></tr>
<tr><td>Materials</td><td colspan="2">Plastics (PE, PP, PVC-U, GRP); Metallic (Steel and Ductile Iron); Concrete based material</td></tr>
<tr><td>Installation methods</td><td colspan="2">Method A: installation by pushing
Method B: installation by pulling
Method C: individual pipe placement</td></tr>
<tr><td rowspan="3">Geometric characteristics</td><td>Diameter range</td><td>Minimum: 100 mm (Methods A and B)
600 mm (Method C)
Maximum: 600 mm (Methods A and B)
4000 mm (Method C)</td></tr>
<tr><td>Maximum length</td><td>150 m</td></tr>
<tr><td>Execution of bends</td><td>Methods A and B: bends can generally not be accommodated ☹
Methods C: bends with large radii can be accommodated ☺</td></tr>
<tr><td>Performance</td><td colspan="2">- Significant reduction in hydraulic capacity due cross section reduction despite less roughness ☹
- Assures pipe structural integrity ☺</td></tr>
<tr><td>Installation characteristics</td><td colspan="2">- Can be applied to most types of pipe ☺
- Rapid installation ☺
- The type of joint is a significant feature of each technique; pipe joints can be locked (end load bearing) or unlocked ☺
- Surface working space: no particular constraint ☺
- Access to the existing pipe requires digging at pipe insertion points ☹
- Reconnection of lateral service connections generally requires excavation ☹</td></tr>
</table>

Legend: ☺ Main advantages; ☹ Main disadvantages.

2.4.4 Close-fit pipe lining

The close-fit pipe lining technique consists of inserting a continuous pipe for which the cross section is prior reduced to facilitate the insertion in the existing pipe and reverted after installation to provide a close fit to the existing pipe (ISO 11295: 2008, EN 15885: 2010). There are two methods for applying this technique, depending on the type of deformation and reversion procedures used:

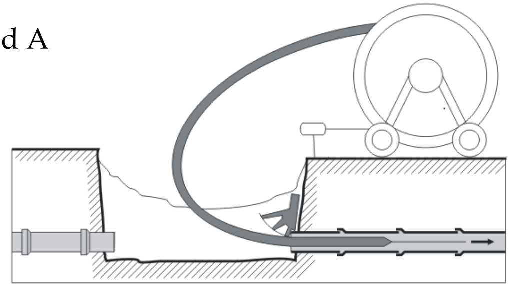
- Method A: **fold and form**

  This process consists of reducing the diameter by folding the liner pipe into a 'U' or 'C' shape prior to installation. This technique is based on either the liner being heated and folded by the manufacturer, then transported to the installation site on a reel or folded on site using folding equipment (Figure 4.4). Typically, the shape is retained by temporary straps and is winched into the host pipe. Once in place, the straps are removed and reversion can be achieved progressively by inserting a rounding device into the upstream end of the liner, which is propelled by steam pressure to the downstream end. As the device progresses, it expands the liner against the wall of the host pipe. Typical liners materials are PVC and HDPE, being the latter the most widely used (Heijn e Larsen, 2004).

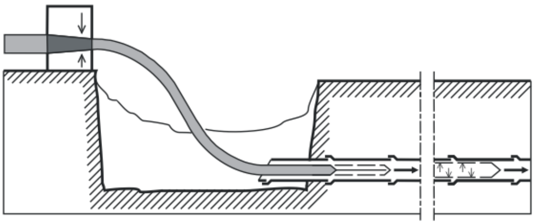
- Method B: **rolldown, drawdown swagelining or deformed/ reformed**

  The rolldown process consists of on-site temporary reduction of the close-fit liner. This is achieved by passing the liner through a set of two concentric rollers which deform its cross section by a mechanical or a thermo-mechanical process before its insertion in the host pipe (Figure 4.4). This process reduces the diameter by 10%. Once the liner is totally inserted, it is gradually reverted back to its original diameter when the winch tension is released, forming a close-fit with the host pipe. This method was originally conceived for renovation of gas pipelines (Heijn e Larsen, 2004). Typically polyethylene (PE) liners are used.

Method A



Method B



The on-site folding process of a HDPE liner is presented as follows:

Folding equipment

Folding process

Strap setting

Folded liner

Pulling head

Close-fit pipe

The main features, conditions of application, advantages and disadvantages of the close-fit pipe lining technique are presented as follows:

<table>
<tr><th>FEATURES</th><th colspan="2">MAIN CHARACTERISTICS</th></tr>
<tr><td>Relevant standards</td><td colspan="2">- EN 13566-1: 2002, EN 13566-3: 2002, ISO/DIS 11296-1, ISO/DIS 11296-3, EN 15885:2010 (wastewater)
- EN 14409-1: 2004, ISO/DIS 11298-1:2008, ISO/DIS 11298-3: 2008 (water supply)
- ISO/DIS 11295:2008 (general)</td></tr>
<tr><td>Materials</td><td colspan="2">Plastics only (PE, PVC-U)</td></tr>
<tr><td>Installation methods</td><td colspan="2">Method A: fold and form
Method B: rolldown, drawdown swage lining or deformed/reformed</td></tr>
<tr><td rowspan="3">Geometric characteristics</td><td>Diameter range</td><td>Minimum: 100 mm (Method A)
200 mm (Method B)
Maximum: 500 mm (Method A)
1500 mm (Method B)</td></tr>
<tr><td>Maximum length</td><td>500 m</td></tr>
<tr><td>Execution of bends</td><td>Bends up to 45° can be accommodated ☺</td></tr>
<tr><td>Performance</td><td colspan="2">- Minimal reduction in hydraulic capacity despite roughness reduction ☹
- Ensures pipe structural integrity ☺</td></tr>
<tr><td>Installation characteristics</td><td colspan="2">- Can be applied to most pipe materials ☺
- Rapid installation ☺
- Energy/effort necessary for the diameter reduction (Method B) significantly increases with the increase of the pipe diameter and wall-thickness
- Working space: Minimum (Method A) ☺; High (Method B) for pipe storage and insertion of the whole pipe length ☹
- Access to the host pipe requires digging at pipe insertion ☹
- Does not require filling space between new and host pipe ☺
- Needs to interrupt supply ☺
- Reconnection of service connections requires excavation ☹</td></tr>
</table>

Legend: ☺ Main advantages; ☹ Main disadvantages.

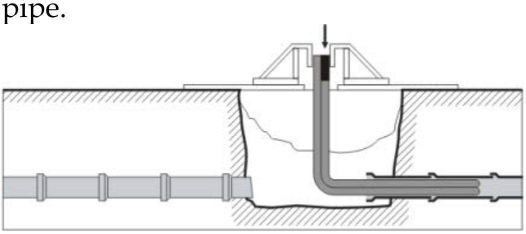
The main advantages of this technique are the possibility to reinforce the resistance of the hosted pipe, the rapid installation, no grouting being necessary and the possibility of liner being installed in host pipes with bends up to 45° (WRc, 2001). The drawbacks are the excavation needed to reconnect the lateral service connections and the surface area needed for pipe storage.

2.4.5 Cured-in-place pipe lining

In the cured-in-place pipe lining (CIPP), a fabric tube is impregnated with a thermosetting resin before insertion into the host pipe. The resin is, then, cured in the host pipe to produce a rigid pipe within the host pipe (ISO 11295: 2008, prEN 15885: 2008).

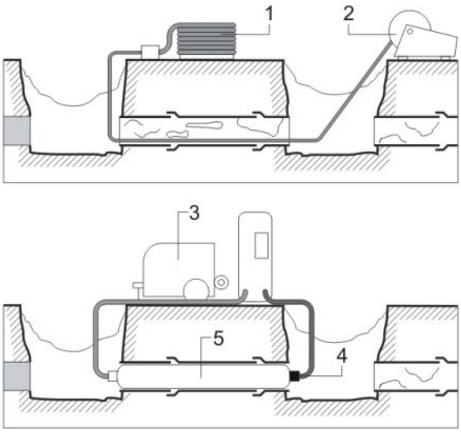
There are several techniques available, according to the process of insertion into the host pipe, being classified into two main types: Method A and B.

Method A, inverted-in-place, uses either water or air pressure to force the resin-impregnated tube through the pipe and invert it, or turn the tube inside out. This process of inversion presses the resin-coated tube against the walls of the host pipe. Heat is then circulated through the tube to cure the resin to form a strong bond between the tube and the host pipe.



Legend
1 – Applied pressure for inversion
2 – Lining pipe
3 – Inversion face

Method B, winched-in-place, uses a winch to pull the tube through the host pipe. After being pulled through the pipe, the tube is inflated to push the liner against the existing walls. Like the inverted-in-place method, heat is then circulated through the tube to cure the resin to form a strong bond between the tube and the host pipe.



Legend
1 – Lining pipe
2 - Winch
3 - End packer
4 – Curing equipment
5 – Renovated pipe

There are innumerable variations, or combinations, of these two methods, being a technique also applicable to service connections.

The application of this technique requires pipe access through valve chambers or entry pits that are excavated for this purpose. A bypass of the flow in the host pipe is usually needed while the liner is being installed. Preparatory cleaning and polishing are need prior to the application of CIPP. After the insertion of the liner, the effectiveness of the method depends on how the impregnated liner adheres to the host pipe. Then, the curing process can be initiated or accelerated by either: ambient temperature; heat (hot water, steam or electrical heating elements); or UV radiation. As result, the curing process forms a strong and impermeable layer in the host pipe.

The combination of the fabric material, with or without fibres, and the resin can be designed to produce a new pipe that has total structural capabilities, semi-structural capabilities or non-structural capabilities (Heijn e Larsen, 2004):

- **Woven hose system**

  This liner is widely used for large diameters when structural integrity of the host pipe has breaks, leaks, internal or external corrosion or faulty joints. These liners can either provide full structural integrity or semi-structural integrity depending on the condition of the host pipe.

- **Felt-based liner system**

  The felt-based liner is made of non-woven polyester felt, coated on one face with a layer of elastomer. This liner can include reinforced fibres to provide full or semi-structural integrity of the liner.

- **Membrane System**

  This membrane is very thin and was initially designed for the rehabilitation of low-pressure gas mains. A membrane system is suitable for non-structural water main rehabilitations and offers internal corrosion protection.

The resins used in water supply systems must meet the requirements (laws and regulations) concerning public health. Moreover, for the use of these techniques, it is necessary to adopt human safety measures, such as breathing protection due toxic gases. This breathing protection measures may include the need of forced air ventilation or protective masks with proper filters (Stein, 2001).

The main **advantages** of this technique include relatively fast installation, reinforce pipe resistance and improved hydraulic capacity, application to a wide variety of diameters and to bends up to 90º, and not needing grouting the annular space.

The main **disadvantages** include the need for specialized staff, the preparatory works have a significant proportion of the total cost, the need for alternative water supply service during the installation and the need to remove and reinstall all subsequent fittings and accessories by local excavation.

The main features, conditions of application, advantages and disadvantages of the CIPP lining technique are presented as follows:

FEATURES	MAIN CHARACTERISTICS	
Relevant standards	- EN 13566-1: 2002, EN 13566-4: 2002, ISO/DIS 11296-1, ISO/DIS 11296-4, EN 15885: 2010 (wastewater) - EN 14409-1: 2004, ISO/DIS 11298-1:2008 (water supply) - ISO 11295: 2008, ISO 25780:2008 (general)	
Materials	A composite consisting of a reinforced or unreinforced fabric carrier material impregnated with thermosetting resin (UP, EP or VE), which can include optional internal and/or external membranes.	
Installation methods	Method A: inverted-in-place installation Method B: winched-in-place installation Combination of Methods A and B are also possible The curing process can be initiated or accelerated by either heat (hot water, steam or electrical heating elements); UV radiation or ambient temperature	
Geometric characteristics	Diameter range	Minimum: 100 mm Maximum: 2800 mm
	Maximum length	600 m (Method A) and 150 m (Method B)
	Execution of bends	Bends up to 90° can be accommodated ☺
Performance	- An improved interior friction coefficient increases hydraulic capacity, even with the slight loss in cross-sectional area ☺ - Nor possible to the installation process ☹ - Possibility to ensure structural integrity (structural, semi-structural, and non-structural applications).	
Installation characteristics	- Rapid installation ☺ - Surface working space: generally minimal, varies with technique ☺ - Access to the host pipe requires digging at pipe insertion ☹ - Does not require filling the space between new and host pipe☺ - Need to interrupt supply ☺ - - Service connections can be reinstalled by robotic cutters, reducing excavation requirements ☹	

Legend: ☺ Main advantages; ☹ Main disadvantages.

A winched-in-place installation is presented as follows:

Lining pipe

Plastic protection

Initiation of lining installation

Lining insertion

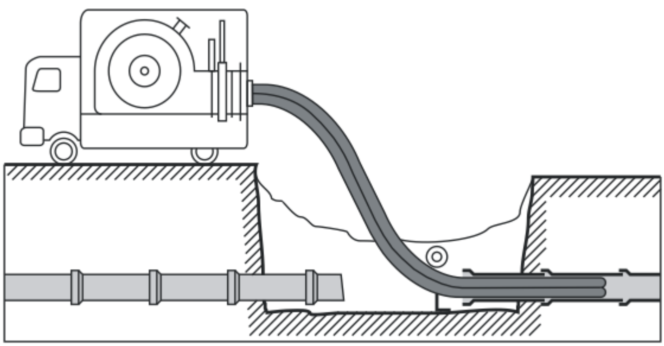
The inverted-in-place is shown as follows:

2.4.6 Lining with adhesive-backed hoses

The lining with adhesive-backed hoses corresponds to lining with a reinforced hose that relies on an adhesive bond to the host pipe to provide resistance to collapse; only semi-structural rehabilitation is possible (ISO 11295: 2008).

The application of this technique requires pipe access through valve chambers or entry pits that are excavated for that purpose. A bypass of the flow in the host pipe is usually needed while the liner is being installed. It is necessary to carry out preliminary cleaning and polishing of the host pipe. The insertion of the adhesive-backed hoses is done by inversion with air and the curing process of adhesive is made by heat with steam. The effectiveness of this technique relies on the adhesion to the host pipe.

The installation of this technique is similar to the previous technique (cured-in-place pipe lining, CIPP) when insertion of the liner is made by reversion into the host pipe. The difference between the two techniques relies on material of the liner. In this technique, the liner only ensures semi-structural resistance while in CIPP the resistance can be structural, semi-structural or non-structural.



The main features, conditions of application, advantages and disadvantages of lining with adhesive-backed hoses technique are presented as follows:

FEATURES	MAIN CHARACTERISTICS	
Relevant standards	- EN 14409-1: 2004, ISO/DIS 11298-1:2008 (water supply) - ISO 11295: 2008, ISO 25780:2008 (general)	
Materials	A circular woven hose of PA, PAN, PEN and/or PET fibres, coated on one side with a thermoplastic (e.g. PE) barrier layer and on the other with a thermosetting resin (UP or EP).	
Installation methods	Insertion of the adhesive-backed hose by inversion with air (heat curing of adhesive with steam)	
Geometric characteristics	Diameter range	Minimum: 50 mm Maximum: 1500 mm
	Maximum length	150 m
	Execution of bends	Bends up to 90° can be accommodated ☺
Performance	- Minimal reduction in hydraulic capacity ☺ - Does not ensure total structural integrity (semi-structural application) ☹	
Installation characteristics	- Surface working space: generally minimal ☺ - Access to the host pipe requires excavation ☹ ☹ ☹ - ☺- Reconnection of lateral service connections generally requires excavation ☹	

Legend: ☺ Main advantages; ☹ Main disadvantages.

The **main advantages** of this technique include fast installation, minimal surface working space requirements, minimal reduction in hydraulic capacity, accommodation of bends up to 90° and no need of grouting the annular space.

The **main drawbacks** include the incapability to reinforce structural resistance of the host pipe, the need for specialized staff, the preparatory works representing a significant part of the total cost, the need for alternative water supply service during the installation and the need to remove and to reinstall all fittings and accessories removed during excavation.

2.4.7 Liners characteristics

Liners should resist to stresses during assembly and installation as well as to internal or external pressure loads during the normal operation. The structural resistance of pressure pipe liners can be classified as follows.

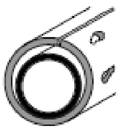
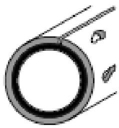
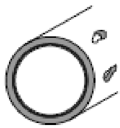
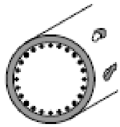
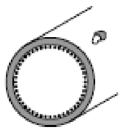
- **Class A:** if the liner is capable to resist without failure to all internal loads throughout its useful life, without relying on the host pipe for radial support.
- **Class B:** if the liner is not capable to resist without failure all to all internal loads throughout its useful life, and therefore relies on the host pipe for some measure of radial support.
- **Class C:** if the liner is capable to resist without failure all to all internal loads jointly with the host pipe but has not enough stiffness to buckling under depressurization.
- **Class D:** if neither the liner nor the host pipe are capable of resisting without failure to all internal loads, being a mere internal barrier layer avoiding leakage.

LINER CHARACTERISTICS/CLASS	A	B	C	D
Can survive internally or externally induced (burst, bending or shear) failure of host pipe	✓			
Long-term pressure rating ≥ maximum allowable operating pressure (MAOP)	✓			
Inherent ring stiffness [1]	✓	✓	(2)	(2)
Long-term hole and gap spanning at MAOP	✓	✓(3)	✓	
Provides internal barrier layer [4]	✓	✓	✓	✓

Notes:

(1) Minimum requirement is for liner to be self-supporting when pipe is depressurized
(2) Relies on adhesion to the host pipe to be self-supporting when depressurized
(3) Becomes sufficiently close-fit for radial transfer of internal pressure stress to host pipe, either during installation or within a short period from initial application of operating pressure
(4) Serves as barrier to corrosion, abrasion and/or tuberculation/scaling of host pipe, and to contamination of pipe contents by host pipe; also generally reduces surface roughness for improved flow capacity

Each of the above mentioned structural resistance classes are associated a renovation technique as shown:

<table>
<tr><th colspan="2">Class A</th><th>Class B</th><th>Class C</th><th>Class D</th></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Loose-fit</td><td>Close-fit</td><td>Inherent ring stiffness</td><td colspan="2">Relies on adhesion</td></tr>
<tr><td colspan="2">Fully structural</td><td colspan="2">Semi-structural</td><td>Non-structural</td></tr>
<tr><td colspan="2">Independent</td><td colspan="3">Interactive</td></tr>
</table>

<table>
<tr><td rowspan="2">Lining with continuous pipe</td><td colspan="2">Close-fit pipe lining</td><td>Lining with adhesive-backed hoses</td><td rowspan="2"></td></tr>
<tr><td colspan="3">Cured-in-place lining</td></tr>
</table>

2.5 Replacement technologies

2.5.1 Types of techniques

The replacement techniques consist of installing a new pipe which substitutes the existing one. This new pipe may keep the alignment or location of the existing pipe being the existing one then deactivated. The replacement techniques can be of two types:

- with open-trench
- trenchless

The **open-trench replacement techniques** may be of two types (Selvakumar *et al.*, 2002, Stein, 2001):

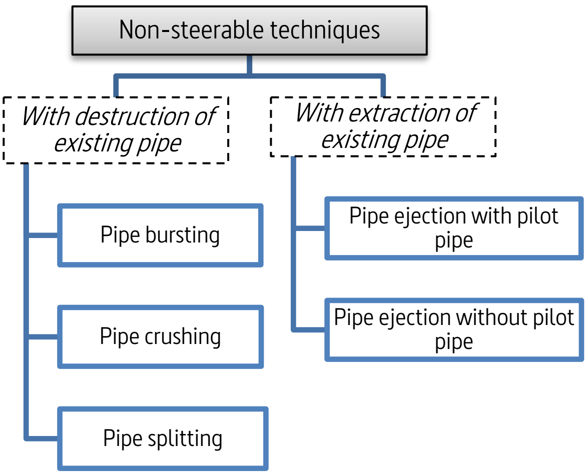
- Conventional open-trench method;
- Narrow trench and mole ploughing.

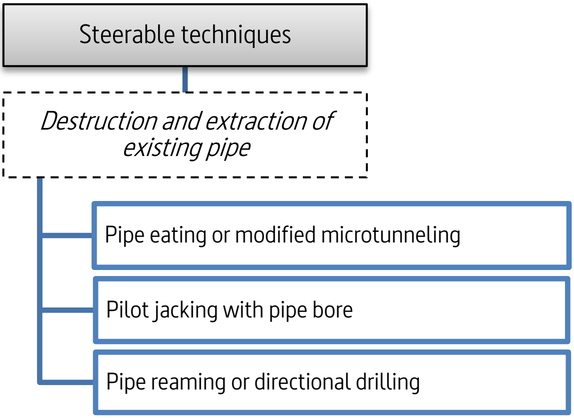
The **trenchless replacement techniques** consist of inserting a new pipe alongside, or near, of the existing pipe with no need of excavating a trench on all its length (digging only on access pits). In general, these techniques use devices that apply forces to the soil or to the existing pipe, continuously or intermittently, by percussion or vibration, from an access pit to another access pit or exit point. The soil and the pipe are displaced or removed on the drilling front (EN 12889: 2000).

These techniques may be applied with minimal perturbation to the intervention area, significantly reducing social and environmental costs arising from the trench opening (e.g. delays due to traffic deviation, losses to local commerce, negative visual impact on touristic places). These are particularly adequate solutions when it is necessary to increase pipe's hydraulic capacity in areas with high traffic where opening a trench is infeasible. Moreover, these techniques also ensure an increment on pipe structural resistance and on its integrity, since the pipe is replaced.

The trenchless replacement techniques can be classified as steerable and non-steerable (EN 12889: 2000). The **steerable techniques** uses control devices (e.g. laser system) to ensure an accurate alignment of the pipe which is necessary to avoid damages to other nearby buried infrastructures. On the contrary, **non-steerable techniques** are applied in situations in which pipe installation with such alignment accuracy is not necessary.

The choice of the most adequate technique depends on the following factors: accuracy required in line and level; proximity of other services; external diameter; length; ground conditions; groundwater conditions and minimum depth of cover (EN 12889: 2000).





In the following sections a detailed description and characterization of each of the above techniques is presented, being highlighted the main differences between the techniques from the same family.

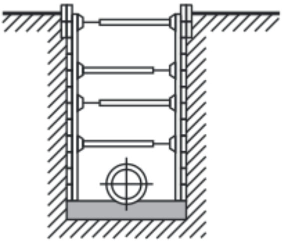
2.5.2 Conventional open-trench technique

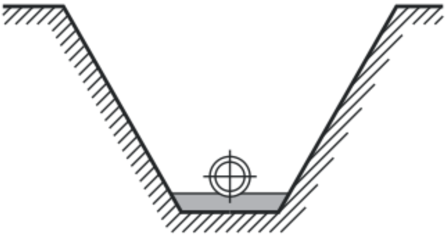
The conventional open-trench technique is the oldest and the most widely used method both to install new pipes and to replace existing pipes. This method consists of digging a trench to lay a new pipe adjacent to the existing pipe, later transferring the service connections to new pipe as a separate operation to minimize interruption of water supply to consumers. When the option is to lay a new pipe over the pipe to be replaced, it is necessary to ensure water supply service alternatives during works execution (e.g., installation of temporary service connections).

The **trench** dimensions (width and depth) and its material composition (thickness and material from the different layers) must comply with the design specifications. These specifications should be in accordance with the applicable laws and standards.

The open-trench replacement technique is widely used. Pipes with different materials, pressure classes and diameters can be installed.

Schematic representations of trenches and some works of open-trench replacement are shown:





The **main features** of this technique are presented:

FEATURES	MAIN CHARACTERISTICS	
Relevant standards	- CSN EN 1610: 1997 (wastewater)	
Materials	Any type of material as long as design requirements are fulfilled	
Installation methods	Insertion of the adhesive-backed hose by inversion with air (heat curing of adhesive with steam)	
Geometric characteristics	Diameter range	No limitations ☺
	Maximum length	No limitations ☺
	Execution of bends	No limitations ☺
Performance	- Possible increment in hydraulic capacity ☺ - Ensures total structural integrity ☺	
Installation characteristics	- Surface working space: generally high ☹ - Negative social and economic impacts due to: high intervention and occupation of public space; noise; vibration; business; circulation of vehicle and pedestrian; need to pavement replacement, etc. ☹ - Costs increase with installation depth ☹ -Reconnection of lateral service connections generally requires excavation ☹	

Legend: ☺ Main advantages; ☹ Main disadvantages.

The **main advantages** are the flexibility regarding dimensions, materials, cross-section characteristics, geological and hydrological conditions, depth, among others. The requirements applicable to the new pipe may be different from the existing pipe. The open-trench replacement technique is more cost effective if the works are carried simultaneously with other infrastructures, especially pavements.

The **main drawbacks** results of significant occupancy of the surface working space that may cause important disturbances in the social and economic activities and in the functioning of other infrastructures. The trench opening may have negative impacts in the nearby structures and infrastructures, especially in consolidated urban areas. Costs may significantly increase due to: the need of adopting measures to remove the excavation material; actions to ensure traffic diversion; the removal and replacement of pavement and the installation of vehicle or pedestrian passages.

2.5.3 Narrow trench technique

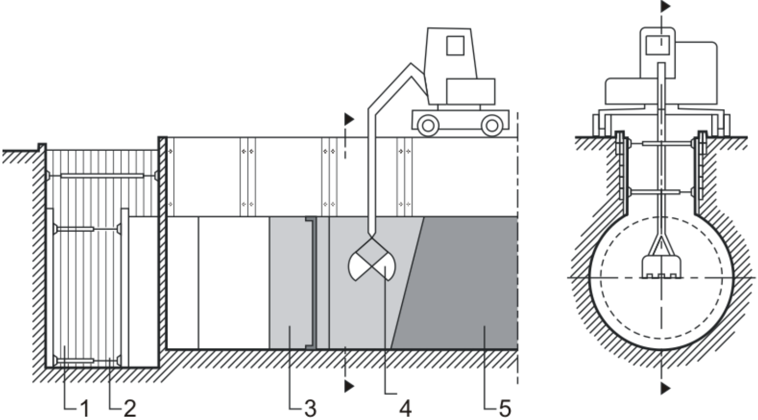
The replacement method with **narrow trench** consists of digging a slight ditch for installing the pipe, aligned with the existing pipe axis. Narrow trench for laying pipes avoids the need for civil workers to enter into the excavated trench and results in less excavated material and disturbances.

Mole ploughing is only used for pulling small diameter pipes through ground, whilst a continuous length of pipe is fed into the top of the plough and buried from the tail.

The new pipe needs to be buffered to avoid the entry of water and soil, being possible to apply this technique without the need of lowering of the water table.

The trench width is reduced to the minimum necessary for removal of the existing pipe and for insertion of the new pipe through its top, depending on the available digging equipment and of the trench depth (Stein, 2001).

The narrow trench replacement technique is shown:



Longitudinal section

Cross section

Legend

1 – Access pit for insertion with a containment system

2 – Pushing system

3 – Section of preparation

4 – Material excavator bucket

5 – Existing pipe

This technique has essentially evolved on the way of opening the trench. It is usually used on cables and small diameter pipe installation in natural ground surface. The installation causes minimal perturbation on the surface during civil works. This technique uses a mole plough which is dragged through the ground (out of the existing pipe alignment), at a desired working depth, by a cable using a tractor. The pipe is inserted through an access pit which is connected to the rear of a blade. The pipe is installed while the blade moves on. This variant of the narrow trench technique does not allow the removal of the existing pipe. Therefore, it is particularly useful for the installation of new pipes.

The **main features** and **condition of applications** of narrow trench and mole ploughing technique are presented as follows:

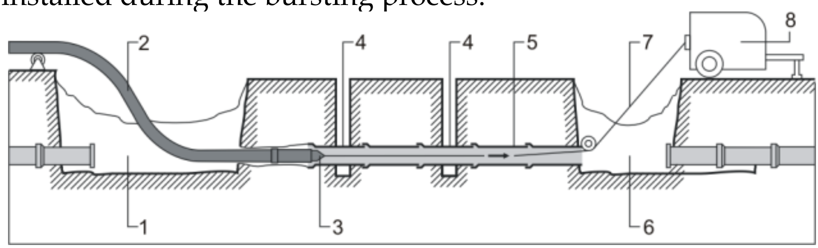
FEATURES	MAIN CHARACTERISTICS	
Relevant standards	CSN EN 1610: 1997 (wastewater)	
Materials	Any type of material as long as design requirements are fulfilled	
Installation methods	Insertion of the adhesive-backed hose by inversion with air (heat curing of adhesive with steam)	
Geometric characteristics	Diameter range	Various (up to 500 mm)
	Maximum length	Depends on the equipment and on diameter
	Execution of bends	Possible
Performance	– Possible increment in hydraulic capacity ☺ – Ensures total structural integrity ☺	
Installation characteristics	– Surface working space: variable but lower than for open-trench technique ☹ – Necessity to excavate an access pit to install the equipment and the new pipe ☹ – Negative impacts associated to the works and to the public space occupation although lower than the open-trench technique ☹ – Installation depth limited to 1.5 m ☹ – Reconnection of lateral service connections generally requires excavation ☹	

Legend: ☺ Main advantages; ☹ Main disadvantages.

2.5.4 Pipe bursting

Pipe bursting is the trenchless replacement method in which an existing pipe is broken either by brittle fracture or by splitting, using an internal mechanically applied force applied by a bursting tool. At the same time, a new pipe of the same or of larger diameter is pulled into the existing pipe, replacing it (Simicevic and Sterling, 2001, EN 12889: 2000, Heijn and Larsen, 2004, NRC, 2003).

The back end of the bursting head is connected to the new pipe and the front end is connected to a cable or pulling rod. The new pipe and bursting head are launched from the insertion pit, and the cable or pulling rod is pulled from the receiving pit. The energy (or power source) which moves the bursting tool forward to break the existing pipe comes from pulling cable or rods, hydraulic power to the head, or pneumatic power to the head, depending on the bursting system design. This energy (or power) is converted into a fracturing force on the existing pipe, breaking it and temporarily expanding the diameter of the cavity. The bursting head is pulled through the pipe debris creating a temporary cavity and pulling behind it the new pipe from the insertion pit. Sometimes an external protective sleeve pipe is installed during the bursting process.

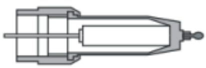


Legend

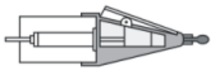
1 – Insertion pit	4 – Temporary bypasses	7 – Puling cable
2 – Replacement pipe	5 – Old pipe	8 – Winch
3 – Expander	6 – Reception pit	

The pipe bursting systems can be classified into three main classes:

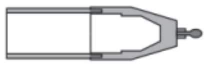
- **Pneumatic pipe bursting** uses pulsating air pressure to drive the head forward and burst the old pipe. A small pulling device guides the head via a constant tension winch and cable.
- **Hydraulic expansion** expands and closes sequentially as it is pulled through the pipe, bursting the pipe on its way.
- **Static pull** has no moving internal parts. The head is simply pulled through the pipe by a heavy-duty pulling device via a segmented drill rod assembly or heavy anchor chain.



Pneumatic system



Hydraulic system



Static pull system

This technique may be applied to replace brittle pipes such as asbestos cement, grey cast iron, concrete and plastic materials. Its use is not recommended to replace pipes of cast iron and steel due to the difficulty to break these materials by burst. In some cases, a cutter and a sharp blade are connected to the bursting head to assist the destruction of more resistant materials.

The **main features** of pipe bursting technique are shown as follows:

FEATURES	MAIN CHARACTERISTICS	
Relevant standards	EN 12889: 2000 ASTM C1208 / C1208M-99a	
Materials	Asbestos cement, grey cast iron, concrete and plastic materials (PE, PVC, PP)	
Installation methods	Pneumatic pipe bursting Hydraulic expansion Static pull	
Geometric characteristics	Diameter range Maximum length Execution of bends	50 – 1200 mm 150 mm (with normal equipment) 400 mm (with high power equipment) Cannot accommodate bends ☹
Performance	- Allows increment in hydraulic capacity ☺ - Ensures structural integrity ☺	
Installation characteristics	- Need of insertion of continuous pipes - No need for preparatory work of cleaning ☺ - High working space required for pipe storage and for the works ☹ - Necessity to excavate an access pit to install the equipment and the new pipe ☹ - Reconnection of lateral service connections requires excavation ☐ - This technique does not rely on adhesion on existing pipe ☐	

Legend: ☺ Main advantages; ☹ Main disadvantages.

Pipe bursting is one of the most advantageous techniques when there are few service connections and fittings, the pipe is much deteriorated structurally and when it is necessary to increase the hydraulic capacity. The pipe diameter can be significantly larger than the existing pipe depending on ground conditions, proximity to other buried infrastructures and the existing pipe backfill.

However, this technique produces vibration levels and land settlements which can affect the nearby infrastructures. The pipe bursting process needs to respect some minimal distances, namely, 1 m from other buried pipes and 2.5 m from buildings. Otherwise, special security measures need to be taken.

Additional application difficulties are those located in: expansive or very hard soils; pipe sections with metallic repair materials; locations where pipe is involved by concrete anchor blocks; and, obstructed pipes. Most of the times, these situations can be solved by site excavations.

Bursting head

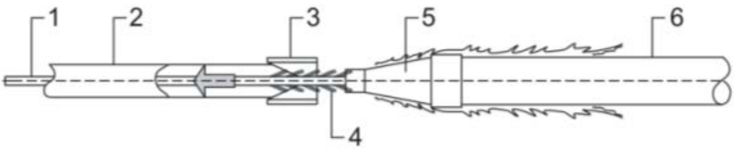
Bursted pipe

Pneumatic equipment

Insertion of a PE pipe

2.5.5 Pipe crushing (or Pipe implosion)

Pipe crushing is a replacement method based on static pull pipe bursting system. In this case, the process begins by "imploding-in" the old pipe followed by pushing the pipe fragments outwards the insertion perimeter (without removing them) and by pipe insertion. The whole process is carried out simultaneously (Simicevic and Sterling, 2001).



Legend

1 – Drive rod string
2 – Existing pipe
3 – Crushing head
4 – Steel blades
5 – Bursting tool
6 – New pipe

The **bursting tool** consists of two parts: a **crushing head** which breaks the existing pipe and forces the pipe fragments inwards into the pipe void, and a **steel cone**, which pushes the crushed pipe fragments and soil outwards, making room for the new pipe. The crushing head is cylinder-shaped, and slightly larger than the existing pipe. Inside the cylinder, there are steel blades, which radially extend from the centre and fracture the old pipe, as the head is pulled forward. The pulling is done with a rod assembly, as in the static pull system.

This technique is **very similar to previous pipe bursting** being especially useful to brittle pipes such as asbestos cement, grey cast iron, concrete and plastic materials. It allows to increase pipe hydraulic capacity as well as to ensure its structural integrity. The pipe diameter can be significantly larger than the existing pipe depending on ground conditions, proximity to other buried infrastructures and the existing pipe backfill.

This technique has application difficulties in some locations with: expansive or very hard soils; pipe sections with metallic materials; or pipes involved by concrete anchor blocks. Most of the times these situations can be solved by site excavations.

However, this technique has the advantage relatively to pipe bursting of not affecting the structural integrity of other nearby infrastructures (e.g. old buildings, sewers).

The **main features** of pipe implosion/crushing technique are presented as follows:

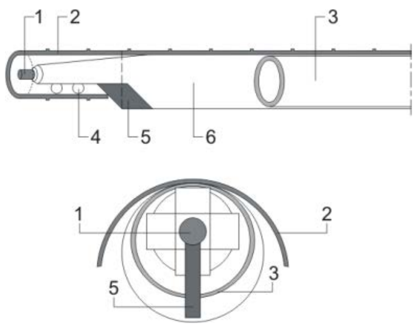
FEATURES	MAIN CHARACTERISTICS	
Relevant standards	None available	
Materials	Asbestos cement, grey cast iron, reinforced concrete and plastic materials (PE, PVC, PP)	
Geometric characteristics	Diameter range	50 – 1200 mm
	Maximum length	150 mm (with normal equipment) 400 mm (with high power equipment)
	Execution of bends	Cannot accommodate bends ☹
Performance	- Allows increment in hydraulic capacity ☺ - Ensures structural integrity ☺	
Installation characteristics	- Need of insertion of continuous pipes - No need for preparatory work of cleaning ☺ - High working space required for pipe storage and for the works ☹ - Necessary excavation for access pits ☹ - Reconnection of lateral service connections requires excavation ☹ - This technique does not rely on adhesion on existing pipe ☺ ☹	

Legend: ☺ Main advantages; ☹ Main disadvantages.

2.5.6 Pipe splitting

Pipe splitting is a replacement method for breaking an existing pipe by longitudinal slitting. At the same time a new pipe of the same or larger diameter may be drawn in behind the splitting tool (Simicevic and Sterling, 2001). Pipe splitting is used to replace ductile material pipes, like steel and ductile iron, which does not fracture using the above-cited bursting pipe and pipe crushing techniques.

This technique uses a splitter which cuts the existing pipe along one line on the bottom and opens it out, rather than fracturing it. The splitter is pulled through the existing pipe by either a wire rope or steel rods and is simultaneously pulled by a pneumatic hammer. The device has a pair of rotary slitter wheels, which make the first cut, a hardened sail blade on the underside of the splitter, which follows, and an expander, whose conical shape and off-centred alignment force the split pipe to expand and unwrap. The splitting and unwrapping of the existing pipe creates a hole immediately behind the splitter large enough to allow the new pipe to be pulled in. The old pipe moves to a position above the hole and the replacement pipe, thus protecting the new pipe from damage.



Legend

1 – Pulling rod	4 – Cutting wheels
2 – Existing pipe	5 – Sail blade
3 – New pipe	6 – Expander

The **main features** of pipe splitting technique are presented as follows.

FEATURES	MAIN CHARACTERISTICS	
Relevant standards	None available	
Materials	Ductile iron, steel	
Geometric characteristics	Diameter range	Variable (depending on power of equipment)
	Maximum length	Variable (depending on power of equipment)
	Execution of bends	Cannot accommodate bends ☹
Performance	- Allows increment in hydraulic capacity ☺ - Ensures structural integrity ☺	
Installation characteristics	- Need of insertion of continuous pipes - No need for preparatory work of cleaning ☺ - High working space required for pipe storage and for the works ☹ - Necessary excavation for access pits ☹ - Reconnection of lateral service connections requires excavation ☹ - This technique does not rely on adhesion on existing pipe ☺ ☹	

Legend: ☺ Main advantages; ☹ Main disadvantages.

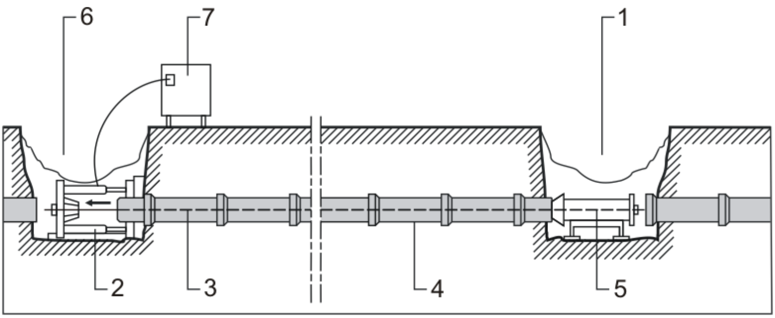
2.5.7 Pipe ejection

Pipe ejection, also known as **pipe extraction** or **pipe pulling**, is a replacement technique in which the existing pipe is extracted by pulling or pushing and simultaneously replaced by a new one (Simicevic and Sterling, 2001, EN 12889: 2000).

This technique has two application methods:

- pipe ejection without pilot pipe
- pipe ejection with pilot pipe

The **pipe ejection without pilot pipe** consists of removing the existing pipe by extraction (**modified static pull**) or by injection (**modified pipe jacking**), while the new pipe is simultaneously installed. The old pipe is broken into pieces only after its removal. This method is applicable only for pipes with sufficient structural resistance to withstand the push or pull forces. It is applied only on shorter replacement sections to avoid high frictional resistance incompatible to the equipment used.



Legend

1 – Entry shaft
2 – Hydraulic pipe pulling device
3 – Pulling rod
4 – Existing pipe
5 – New pipe
6 – Exit shaft
7 – Hydraulic pump

The **pipe ejection with pilot pipe** consists of drilling ground by outer surface of the pipe (without pipe removal or breaking) and simultaneously a new pipe with a higher diameter is inserted, without destructing the old pipe. The cutting head allows a concentrically installation between both pipes (i.e. the new and the old one). The old pipe leads the new one and ensures that its installation follows the original alignment. Pilot pipe jacking may be dynamic (impact) or static (compression). When the existing pipe is totally evolved by the new pipe, the tops of the old pipe are sealed and it is pulled out. The old pipe is extracted in fragments thus it arrives to the entry shaft.

The main features of this technique are presented as follows.

FEATURES	MAIN CHARACTERISTICS	
Standards	None available	
Materials	Any, since pipe structural resistance is guaranteed.	
Installation methods	- Pipe ejection without pilot pipe ✓ Modified static pull / Modified pipe jacking - Pipe ejection with pilot pipe ✓ Dynamic (by impact) / Static (by compression)	
Geometric characteristics	Diameter range	Variable (depending on equipment)
	Maximum length	Variable (depending on equipment)
	Execution of bends	Cannot accommodate bends ☹
Performance	- Allows increment in hydraulic capacity ☺ - Ensures structural integrity ☺	
Installation characteristics	- Need of insertion of continuous pipes - No need for preparatory work of cleaning ☺ - High working space required for pipe storage and works ☹ - Necessity to excavate access pits at pipe ends ☹ - Reconnection of service connections requires excavation ☹ - This technique does not rely on adhesion on existing pipe ☺ ☹	

Legend: ☺ Main advantages; ☹ Main disadvantages.

2.5.8 Pipe eating or modified microtunnelling

Pipe eating or modified microtunnelling is a technique that uses a specially-designed variation of a microtunnelling machine, which excavates the old pipe in fragments and removes them rather than displaces them, and jacks the new pipe into the place as in a microtunnelling operation. The system is remotely controlled and guided with a surveyed laser beam from the drive pit (Simicevic and Sterling, 2001, Heijn and Larsen, 2004, Selvakumar *et al.*, 2002, EN 12889: 2000).

This technique has two application methods:

- microtunnelling
- pipe jacking with pipe bore

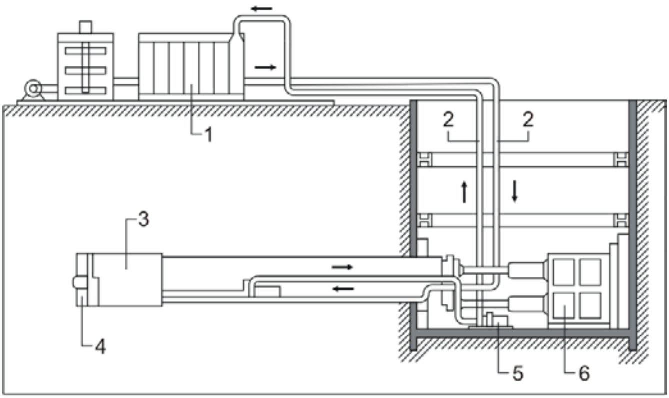
In **microtunnelling** the existing pipe is crushed and removed through the new pipeline by the circulating slurry system. A new pipe is simultaneously installed by jacking it behind the microtunnelling machine. The new pipe may follow the line of the old pipe on the entire length, or may move away from it in located zones.

Pipe jacking with pipe bore is a multi-phase method. In the first phase a steered rigid pilot pipe is accurately installed. In subsequent phases, the pilot bore is enlarged and the pipes installed by soil displacement or soil removal methods (EN 12889: 2000).

The controlling process of the cutting head direction on drilling rig is done by a laser beam. Any deviations in direction of the cutting head can be immediately corrected. For that reason, this technique is the most accurate among other trenchless methods to replace pipes (errors lower than 2.5 cm). This fact is of utmost importance when the installation ground is crowded by other infrastructures (Selvakumar *et al.*, 2002).

This technique was first developed in Japan at the seventies to replace sewers in urban areas. Nowadays, it is widely used to install pipes in urban areas with high depths or to replace pipes with different profiles or layouts from the old pipe. It can be used in highways or railways crossings and in areas with many buried infrastructures.

The microtunnelling applied to pipe replacement uses a drilling rig combined with others from pipe fragments removal and pipe installation. The drilling rig is remotely controlled and guided with a surveyed laser beam, and is prepared to "eat" whatever is in the way. Is constituted by a cone-shaped cutting head, with teeth and rollers, and by a shield section that carries the cutting head and its hydraulic motor system



Legend

1 – Sludge storage tank	2 – Sludge pipes	3 – Shield
4 – Cutting head	5 – Sludge removal pump	6 – Tunnelling engine

Different pipe fragments' removal methods may be used. These methods correspond to variations of the technique:

- **microtunnelling with auger spoil removal:** An auger is used for removal of spoil
- **slurry shield microtunnelling:** a slurry system is used for removal of spoil
- **microtunnelling spoil removal by vacuum:** a vacuum system is used for removal of spoil
- **microtunnelling spoil removal by other mechanical means:** mechanical systems other than those above are used for removal of spoil
- **microtunnelling incorporating pipe eating:** an existing pipe is excavated together with surrounding ground. The microtunnelling machine incorporates crushing or cutting capability. Spoil can be removed by an auger or slurry system

This technique may be used in all soil types (from clay to hard rock), simply by using the most appropriate cutting head. The jacking forces transmitted from the drilling rig to the pipe drives the cutting head, producing a controlled progression. It can be used to depths up to 30 m. The installed pipes may be of concrete, steel, ductile iron, glass fibre reinforced plastic (GFRP) and PVC.

The **main features** of this technique are presented as follows:

FEATURES	MAIN CHARACTERISTICS	
Relevant standards	- EN 12889: 2000 - ASCE 36-01 Standard constr. guidelines for microtunnelling (ASCE, 2001) - ASTM C1208 Standard specification for vitrified clay pipe and joints for use in microtunnelling	
Materials	Concrete, steel, ductile iron, GFRP, PVC	
Installation methods	- Microtunnelling - Microtunnelling with auger spoil removal - Slurry shield microtunnelling - Microtunnelling spoil removal by vacuum - Microtunnelling spoil removal by other mechanical means - Microtunnelling incorporating pipe eating - Pipe jacking with pipe bore	
Geometric characteristics	Diameter range Maximum length Execution of bends	150 – 2500 mm 200 m Cannot accommodate bends ☹
Performance	- Allows increment in hydraulic capacity ☺ - Ensures structural integrity ☺	
Installation characteristics	- Need of insertion of continuous pipes - High working space required for pipe storage and for the works ☹ - Necessity to excavate access pits at pipe ends ☹ - Reconnection of lateral service connections requires excavation ☹ - This technique does not rely on adhesion on existing pipe ☺ - May affect structural integrity of nearby infrastructures (e.g. old buildings) ☹	

Legend: ☺ Main advantages; ☹ Main disadvantages.

Some constructive aspects of microtunnelling are shown as follows:

Entry shaft

Cutting head

Pipe section installation

Initiation of pipe pushing

Pipe pushing

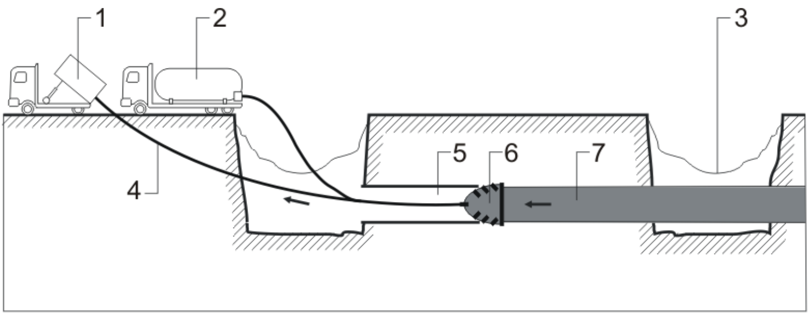
Exit shaft, head arrival

2.5.9 Pipe reaming or directional drilling

Directional drilling is a steerable system for the installation of pipes using a drilling rig. When specifically applied to pipe replacement, this technique is called **pipe reaming**.

A **pilot bore** is drilled using a steerable drilling head pushed by flexible rods. The bore is then enlarged by reamers up to the diameter required for the pipeline and, then, the pipe or pipes are pulled /pushed into place (Simicevic and Sterling, 2001, EN 12889: 2000, Selvakumar *et al.*, 2002).

This technique is a **multi-phase method** being directed from surface. First, the pilot drill string with a suitable-size is inserted through the existing pipe. Next, a specially designed reaming tool is attached to the drill string and pulled back through the pipe, while simultaneously installing the new pipe. The reamer has cutting teeth, which grind and pulverize the existing pipe through a "cut and flow" process, rather than a compaction. The pipe fragments and the excess material from upsizing are carried with the drilling fluid to access pits, and retrieved with a vacuum truck or slurry pump for disposal (Heijn and Larsen, 2004).



Legend

1 – Drilling rig	3 – Insertion pit	6 – Reaming head
2 – Sludge aspiration	4 – Drill pipe	7 – New pipe
	5 – Existing pipe	

The main differences between pipe drilling and microtunnelling lay on how pipe is wrecked and the system control mode. The former wrecks the old pipe and enlarges the drill bore replacing the reamers by steps while the latter the old pipe is wrecked all at once. Relatively to the system control mode, the former is directly controlled from the surface while the latter is controlled remotely.

This technique is widely adopted to install new pipes when an open-cut excavation is unsuitable (e.g. road or railway crossing). Most frequent pipe materials used are PE, steel, ductile iron and PVC (Heijn and Larsen, 2004).

The **main features** of pipe reaming or directional drilling technique are presented as follows:

FEATURES	MAIN CHARACTERISTICS	
Relevant standards	EN 12889: 2000	
Materials	PE, steel, ductile iron, PVC	
Geometric characteristics	Diameter range	100 – 1200 mm
	Maximum length	500 m (depending on pipe diameter)
	Execution of bends	Cannot accommodate bends ☹
Performance	- Allows increment in hydraulic capacity ☺ - Ensures structural integrity ☺	
Installation characteristics	- Need of insertion of continuous pipes - High working space required for pipe storage and works ☹ - Necessity to excavate access pits at pipe ends ☹☐ Reconnection of service connections requires excavation ☹ - This technique does not rely on adhesion on existing pipe ☺ ☹ - May affect structural integrity of nearby infrastructures ☹	

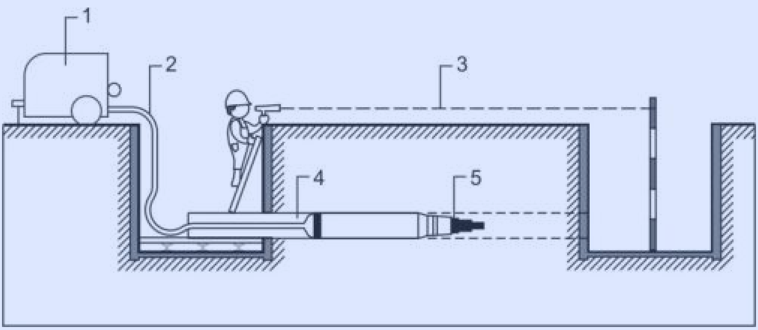
Legend: ☺ Main advantages; ☹ Main disadvantages.

2.5.10 Other non-steerable techniques

There are a set of other non-steerable trenchless techniques that are especially used in sewers installation (EN 12889: 2000) and some of them may be used as well in water pipes. These techniques are particularly recommended for the installation of new water pipes which do not involve the destruction of the existing pipe.

SOIL DISPLACEMENT TECHNIQUES

- **Impact moling** uses a tool which comprises a percussive hammer (pneumatic or hydraulic) within a casing, generally a cylinder with tapered nose or stepped head which travels through the ground. Its forward movement displaces the soil and relies on the frictional resistance of the ground. A pipe is pulled or pushed either immediately behind the impact moling tool or through an unsupported bore which may be formed in suitable ground.



Legend

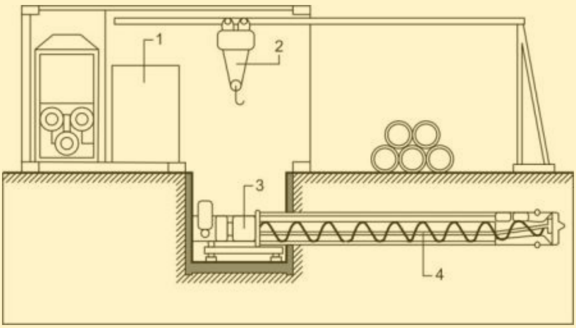
1 – Hydraulic pump/air compressor
2 – Air hose
3 – Vision line
4 – Casing
5 – Percussive hammer

- **Pipe ramming with a pipe closed at its leading edge** is a technique of forming a bore by driving a steel casing with a closed end using a percussive hammer. The ground is displaced by the closed end.

- In the **pipe ramming with expander**, the ground is displaced by pushing a rigid pilot rod. The pipe is installed by pulling or pushing behind an expander.

SOIL REMOVAL TECHNIQUES

- **Pipe ramming/pushing with an open ended pipe** is a technique of forming a bore by driving a steel casing with an open end using a percussive hammer or pushing device. The spoil is removed by augering, jetting, compressed air or high pressure water.
- **Hammer drilling** uses a percussive hammer mounted at the cutting head in the excavated bore with or without a sleeve. The spoil is mechanically removed by water or compressed air.
- In the **rod pushing with a reamer**, the soil is displaced by pushing a rigid pilot rod. The new pipe is installed by pulling it behind a rotating reamer.
- In the auger boring, the soil is excavated by a rotating cutting head attached to an auger which continuously removes the spoil. Pipe is simultaneously pushed with and independently from the auger.



Legend

1 – Control console
2 – Hoists
3 – Pushing/boring system
4 – Cutting head with auger

The installation of a new pipe to reinforce the existing system using the auger drilling technique is presented as follows:

Rotating cutting head with auger

Soil boring and new pipe installation

Pipe welding

2.6 Selection of appropriate pipe rehabilitation technique

2.6.1 Methodology

In the previous sections the most used pipe rehabilitation techniques were described. Bearing in mind that the choice of a technique has to take into account the specific local aspects, a methodology to select the most appropriate technique is presented.

The procedure to select the most appropriate pipe rehabilitation technique includes the following main steps (ISO 11925: 2008):

- assessment of existing pipe features and of its actual performance deficiencies (anomalies);
- identification of main requirements to achieve expected performance;
- identification of possible techniques and respective cost, advantages and disadvantages;
- comparison and selection of appropriate technique.

In the following sections a description of the previous steps is presented, according to ISO 11295: 2008 standard. A table summarizing the main features and advantages of each described technique is shown at the end.

2.6.2 Assessment of existing pipe features and main deficiencies

In a first stage, a **survey of basic information** about the pipe to be rehabilitated should be carried out, namely:

- material;
- pressure class;
- diameter;
- joint types;
- fitting types;
- fluid physical and chemical characteristics;
- historical of observed anomalies and its types.

Afterwards, and depending on diameter and on the importance of pipe to be rehabilitated, a **visual inspection**, using for example a CCTV, can be carried out. This inspection should register in a systematic way all observed deficiencies and components (e.g. fittings and joints). The assessment of severity of each observed deficiency can take into account:

- geometric pipe features (e.g. diameter change, pipe ovalisation, axial and radial displacement);
- hydraulic pipe condition (e.g. leakage, incrustation);
- structural condition (e.g. burst, corrosion).

Finally, the **characterisation of site conditions** affecting installation should be undertaken, namely:

- access to the existing pipe (e.g. depth, existence of access pits or excavation requirement, surface area availability, traffic existence, proximity to other infrastructures);
- works restrictions (e.g. depth of groundwater level, distance between access pits, directions changes, joints, valves, service connections; existence of water service alternatives).

2.6.3 Identification of main requirement

According to the type of problem found the main requirements of rehabilitation technique should be specified. Examples of the **main anomalies observed and necessary requirements to improve performance** are presented in the following table. For each situation, more than one anomaly can be identified, and, therefore, one or more requirements can be defined.

ANOMALY	REQUIREMENTS
Water quality	– -need for pipe insulation to prevent reactions between pipe walls and the fluid conveyed (e.g. internal corrosion due aggressive water or incrustations due water hardness) – - increase of flow velocity (high time of retention)
Hydraulic	– - increase of hydraulic capacity through pipe cleaning or reduction of pipe wall roughness (e.g. useful cross-section reduced due high rate of incrustation) – - significant increase of pipe hydraulic capacity relatively to its initial situation with the need of diameter increase (e.g. high head losses for the existing diameter and insufficient pressure)
Structural	– - increase of pipe structural resistance (e.g. reduced pipe thickness due corrosion or necessity of pressure increase) – - sealing of leaks, cracks or existing opened joints in the pipeline to avoid water losses or contamination
O&M	– - associated to topology, no need to increase the number of control devices and equipment of measure

2.6.4 Identification of possible techniques

This step consists of determining the different rehabilitation options according to the specified requirements for the analysed situation. Different decision models, more or less simplified, exist to select the most appropriate technique (NRC, 2003).

Some examples of the **requirements necessary to improve performance according to the problem type** are shown. For each situation, the feasible rehabilitation techniques are presented.

PROBLEM TYPES	REQUIREMENTS	REHABILITATION TECHNIQUES
– High rate of tuberculation or incrustation, causing water quality problems or hydraulic capacity reduction in a structurally robust pipe	– Pipe insulation – -Pipe hydraulic capacity increase (being the existing diameter sufficient)	– - Coating or spray-lining – - Cured-in-place pipe lining – - Lining with adhesive-backed hose
– Defective joints or local corrosion causing high water losses in a structurally robust pipe	– Pipe insulation – Sealing of leaks, cracks or open joints	– - Internal joint seals – - Cured-in-place pipe lining – - Lining with adhesive-backed hose
– High corrosion rate with loss of structural resistance, causing pipe deterioration, high water losses and frequent bursts	– Pipe structural resistance increase – Pipe insulation	– - Conventional sliplining – - Close-fit pipe lining – - Cured-in-place pipe lining – - Pipe bursting, pipe crushing or pipe splitting – - Pipe ejection or pipe extraction – - Pipe eating or modified microtunneling – - Directional drilling
– Insufficient pipe section, needing to increase hydraulic capacity in a pipe with loss of structural resistance	– Pipe hydraulic capacity increase (need to increase pipe diameter)	– - Conventional open-trench – - Narrow trench – - Pipe bursting, pipe crushing or pipe splitting – - Pipe ejection or pipe extraction – - Pipe eating or modified microtunneling – - Directional drilling
– Insufficient pipe section, needing to increase hydraulic capacity in a structurally robust pipe	– Pipe hydraulic capacity increase (need to increase pipe diameter)	– - Same as above – - No pipe direct intervention, but adopt reinforcement options (e.g. creating connections to other zones, pipe duplication without deactivation)

2.6.5 Comparison and selection of appropriate technique

After the identification of possible rehabilitation techniques to be used, the final option is assessed by the domain of application of each one (i.e. diameters, depth and materials). This assessment should take into account other variables in the decision process (e.g. existence of bends and fittings, presence of service connections, working space requirements). Furthermore, the advantages and drawbacks of execution and costs of each technique should be compared.

The most appropriate technique is not always obvious and, for the same rehabilitation problem, may vary from country to country, even from continent to continent. Sometimes it depends on the existing equipment and qualified staff for the application of the technique. Moreover, it also depends on the existence of constructor for the use of that type of technique.

The open-trench is still the most frequent rehabilitation technique, whilst other techniques are adopted motivated by population reasons (e.g. minimization of traffic interruptions in high traffic areas or minimization of local commerce disruptions) or imposed by other infrastructures utilities (e.g. impossibility of new pavement removal during five years imposed by municipality or prohibition to use open-trench techniques to perform road-crossings imposed by national road authority).

The main features of each technique are summarized as follows. A cost estimation is also presented based on the study carried out. Finally, the last column shows a qualitative classification of costs based on execution difficulty and sophistication of the equipment needed.

Technique (method)	Non structural resistance	Semi-structural resistance	Structural resistance	Hydraulic capacity	Typical diameter range (mm)	Typical maximum length (m)	Bends accommodation	Surface working space required	Cost (€/cm of diameter /m of length)	Qualitative cost
Renovation										
Internal joint seals	✓			=	250-6000	200	-	+		€
Coating or spray-lining A: Mechanical application B: Manual application - cement mortar - epoxy	 ✓ ✓			 ↗ ↗	 200 - 600 ≥ 1600	 100 No limitation.	No limitation	+	 3–8[3] 23–38[3]	 € €€
Lining with continuous pipe			✓	↓	100 - 2000	300	Difficult	+/++	10–15[3]	€€
Lining with discrete pipe - pushing or pulling - combined			 ✓ ✓	 ↓ ↓	 100 - 600 600 - 4000	 150 150	Di	+		€€
Close-fit pipe lining - fold and form - rolldown		 ✓ ✓	 ✓ ✓	 ↗ ↗	 100 - 500 200 - 1500	500	up to 45°	 + ++	10–15[3]	€€
Cured-in-place pipe lining A: inverted-in-place B: winched-in-place - woven hose system - felt-based liner system - membrane System	 ✓	 ✓ ✓	 ✓ ✓	↗	 100 - 2800 100 - 2800 - - -	 600 150 -	up to 90°	+	15–35[3]	 €€€ €€€ €
Lining with adhesive-backed hose		✓		↗	50 - 1500	150	up to 90°	+		€€
Replacement										
Open-trench			✓	↑	No limitation	No limitation	No limitation	+++		€€
Pipe bursting			✓	↑	50 -1200[1][2]	150[1], 400[2]	Difficult	++	18–23[3]	€€€
Pipe crushing			✓	↑	-	-	Difficult	++		€€€
Pipe splitting			✓	↑	-	-	Difficult	++		€€€
Pipe extraction			✓	↑	-	-	Difficult	++		€€€
Modified microtunneling			✓	↑	300 - 3000[1] 200-2500[4]	200[1]	Difficult	++	40 - 60[3]	€€€€
Directional drilling			✓	↑	100 - 1200[1]	500[1]	Difficult	++	25 – 63[3]	€€€€

Legend: ↑ substantial increase; ↗ medium increase; = preserves; ↓ substantial decrease
+ minimum; ++ average; +++ high; € low cost; €€€€ high cost
[1]NRC (2003); [2]Simicevic e Sterling (2001); [3]Selvakumar *et al.* (2002); [4]Orchard (2006)

Rehabilitation techniques for storage tanks

3

3.1 Anomalies classification

Storage tanks are facilities provided to ensure the reliability of supply, to maintain pressure, to reduce the size of transmission mains, and to improve operational flexibility and efficiency.

Main purposes of storage tanks are to balance the hourly demand variations, to maintain constant pressure in the distribution mains, and to guarantee fire and emergency storage. Tanks can be of **different types** such as, underground (or buried), ground level or elevated (or overhead) tanks. According to the **storage capacity** they can be classified as small (< 500 m^3), medium (500-5000 m^3) or large (> 5000 m^3).

Storage tanks are composed of a larger component of civil works and of another smaller part of eletromechanical and electric equipment (e.g. shutoff valves, control valves and electric boards). Typically, they are made of reinforced concrete, so many of the observed structural anomalies leading to rehabilitation are similar to the ones of other infrastructures of reinforced concrete (e.g. cracking, corrosion, settlements…).

Since tanks stores treated water for distribution, sealing materials need to be used to ensure water-tightness. These materials cannot, in any circumstance, release hazardous and noxious substances to public health.

Some examples of **anomalies** are:

- lack of water-tightness due foundations deficiency (i.e. differential settlements) or of waterproofing (i.e. inadequate waterproofing due to chemical water composition);
- loss of structural resistance due to construction deficiency (e.g. deficient joint execution resulting in horizontal cracking, insufficient reinforcement backfill, deficient joining of the sidewall to the floor or to the cover, deficient concrete application or vibration on specific areas).

The construction of storage tanks should be guarantee structural resistance and water-tightness. The floor should have a slope of at least 1% for gutters or discharge devices.

Storage tanks should be placed out of service for maintenance having for that a bypass or more than one compartment. These compartments (at least two) should be interconnected but prepared to operate independently (except for elevated tanks). Each compartment should have, at least, a supply circuit with a shutoff valve at the inlet, a distribution circuit with a shutoff valve and the inlet protected by a strainer, an emergency circuit with a top outlet discharge and an emptying and cleaning circuit with a bottom outlet discharge. Additionally, storage tanks should have adequate ventilation and easy access to its interior.

Oftentimes, these and other constructive aspects are not complied (EN 1508: 1998), which results into a premature need of rehabilitation associated to water quality anomalies (e.g. existence of stagnant areas) or to operation and maintenance anomalies (e.g. single compartment without bypass to perform cleaning operations with no water service interruption). Other anomalies resulting from not foreseen situations or foreseeable in project may be found, such as structural or water quality problems due characteristics changes of the abstracted water, or hydraulic problems due to demand increases.

The **anomalies** can be classified as structural, hydraulic, water quality and operation and maintenance depending on its nature. **Some types of anomalies** in storage tanks leading to rehabilitation are presented as follows according to its nature. The **main causes and solutions** are also presented.

NATURE	ANOMALY TYPE	MAIN CAUSES	SOLUTIONS
Structural	Loss of structural resistance	– Project inaccuracies – Deficient construction works – Differential settlements – Underground interventions – Damages caused by third parties – Material corrosion/lixiviation – Landslide – Earthquakes	– Reconstruction or reinforcement of parts – Full replacement
	Lack of water-tightness (cracks and leaks)		– Waterproofing – Interior and exterior painting
Hydraulic	Insufficient hydraulic capacity	– Incorrect design or project – Change of operating conditions – Change of demand – Other storage tanks deactivation	– Construction of additional compartments incorporating or not the existing (system expansion)
Water quality	Deficient working condition (existence of stagnant areas)	– Design or project inaccuracies (incorrect internal configuration or hydraulic circuit)	– Construction of septum at the inside of the compartments – Installation of new hydraulic circuits
		– Change of water source or of physical-chemical water characteristics – -Change of operating conditions – -Change of demand	– Installation of new hydraulic circuits – Alteration of O&M practices (e.g. chlorine addition or increase cleaning frequency)
Operation and maintenance	O&M difficulties (cleaning difficulties, ensuring water service)	– - Inadequate number of compartments or inexistence of a bypass circuit	– Construction of additional compartments – Construction of a bypass circuit

3.2 Types of rehabilitation interventions

The interventions of potable water storage tanks may be of different types such as maintenance, renovation, replacement and expansion. Maintenance and expansion are not considered as rehabilitation interventions. Renovation interventions can be subdivided as non-structural renovations if the structural resistance of the storage tank is not ensured (e.g. waterproofing, painting) and as structural if structural resistance is ensured (e.g. floor or foundation repairs).

There are also other interventions on storage tanks associated to preventive renovation that uses some rehabilitation technologies but which are not rehabilitation interventions (e.g. storage tank coating to avoid water quality degradation).

The main interventions on storage tanks are presented as follows:

TYPE OF INTERVENTION			INTERVENTIONS
Maintenance		NR	✓ -Cleaning and disinfection ✓ -Inspection ✓ -Waterproof test
Renovation	Non-structural renovation	R	Internal and external painting: ink removal, surface preparation and ink application ✓ Epoxy treatment
		R	Internal and external coating: removal, surface preparation and application including anticorrosive protection of armouring ✓ Cracks repair ✓ Armouring at sight repair ✓ Repair with waterproof mortar ✓ Floor and coverage repairs Expansion joint repair ✓ Inner access ladder repair ✓ Repair of concrete external surface ✓ Coverage waterproofing ✓ Outer access ladder repair
		R	- Construction of new hydraulic circuits - Construction of new building components (septum)
	Structural renovation	R	-Change of foundation, bedding, floor, coverage or structure (pier)
		R	-Replacement of equipment, fittings (e.g. ladders, ventilation system, discharge system)
		R	-Reinforcement of the steel equipment welding
Replacement		R	-Deactivation and replacement
Expansion		NR	-Construction of new compartments and of its hydraulic circuits

Legend: **R** = Rehabilitation intervention; **NR** = Non-rehabilitation interventions

3.3 Coating solutions

3.3.1 Introduction

One of the main problems associated to reinforced concrete storage tanks is the **oxidation of the reinforcing steel**. Thus, most rehabilitation interventions aim to protect the concrete using materials that prevent oxidation of the reinforcement. This protection can be made either by physical insulation of the concrete wall or by chemical filling, promoting an alkaline environment with an inhibitory effect of iron oxidation.

The coatings used in reinforced concrete elements may be of three different types:

- cement mortar of high compactness
- epoxy resin
- polyurethane or polyuria

Each of these types of coatings is described in the following sections as well as their main advantages and drawbacks.

3.3.2 Cement mortar of high compactness

A **cement mortar** of high compactness is characterized by the use of a hydraulic binder of cement and fine aggregate (sand) with a continuous grain-size distribution. This distribution is very specific in order to fill all interstitials ensuring a high compactness of the material.

Sometimes a gel to fill the smaller interstitials is added. This mortar should be applied at a thickness suitable to the surrounding environment characteristics, ranging from 5 to 20 mm. For example, in mortars contacting very aggressive water, the destruction of the surface layer can reach thicknesses of 15 mm.

The coating with this type of mortar has the double effect of ensuring the physical and chemical protection of the concrete. On one hand, the mortar constitutes a physical barrier that hinders the chemical agents that will attack the concrete of penetrating and attack the reinforcement. On the other hand, promotes a highly alkaline environment (increasing the Ph of the concrete) with an inhibitory effect of the oxidation phenomenon of the reinforcement iron.

The use of this type of covering has the main advantage of presenting a similar behaviour as the concrete. Consequently, the set of mortar-concrete behaves as a single block element towards deformation due to temperature variation, ground settlement, earthquakes or several loads. For that reason, the likelihood of detachment of the mortar of concrete is very low. Other advantages are its low cost and easy application. It can be applied to any surface type – wall, pillar, bottom slab and ceiling.

However, this technique has as the drawback of being a slight flexible material, and thus not recommended to surfaces with large cracks or high mechanical or thermal deformations. In these cases, one of the following solutions should be chosen.

3.3.3 Epoxy resin

The **epoxy resin coating** requires a surface preparatory work to assure an adequate adhesion (i.e. requires a clean, dry and adequate base). This preparatory work consists of cleaning the surface to rehabilitate and application of a mortar primary layer which regularizes and standardizes the surface. Afterward, one or more layers of epoxy resin are applied until the desired thickness.

The main **advantages** of this solution are its low cost, surface high resistance to chemical attack (e.g. chlorine) and high ease of surface cleaning with a nozzle which is very important to regularly clean the water storage tank.

The **main drawback** comes from the full waterproofing of the applied coating and therefore retains water bubbles of concrete condensation or by infiltration coming from the outside. These bubbles lead to loss of adhesion of the coating to the concrete and, ultimately, may burst unprotecting the concrete. Often some solutions are mistakenly adopted such as increasing the thickness of epoxy resin layer to avoid bubbles. This solution is ineffective since it does not prevent bubble formation and covers the loss of adhesion of the concrete material. For that reason, these solutions should not be used on storage tanks roofs which are very susceptible to water infiltration from the outside that tends to be retained within the coating.

3.3.4 Polyurethane or polyuria

Polyurethane and **polyuria** are copolymers which mean that these are materials resulting from joining two or more mono-polymers. The application of these materials for coating is similar to the previous solution of epoxy resin. It requires always a clean, dry and homogeneous application surface and it may require the previous application of a primary layer of mortar. It has the same advantages and drawbacks of coating with epoxy resins. However, this coating solution has high elasticity and durability (higher than epoxy resins). Its main drawbacks are the high cost that can reach more than double the previous technique and some difficulty of application. Nowadays, hybrid coatings that combine polyurethane with polyuria start to appear in the market.

Note that the three types of coatings may be used in walls, pillars, bottom slabs and beams. However, only the first type (cement mortar) may be used in ceilings. The reason for that is its porosity that allows drainage of the condensed water on concrete and avoids the formation of bubbles which are typical of the other two types of coatings which are totally waterproof.

3.4 Final remarks

Upon completion of the rehabilitation work, the disinfection of the storage tank and of the associated gutters is necessarily. Subsequently, lab analyses to the stored water are carried out to verify the water quality parameters.

The products to be applied to coating the surfaces should take into account drinking water quality parameters. In any circumstances, these may not release harmful substances to public health. Therefore, the used should be of food quality for drinking water.

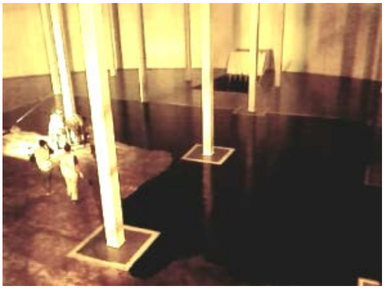
The following figures show some examples of anomalies observed in storage tanks of reinforced concrete and rehabilitation interventions.

Coverage cracks: before and after repair with cement mortar

Structure of a storage tank with armour in sight (before repair)

Removal of outside coating and storage tank waterproofing (after repair works)

Repair of the storage tank bottom slab



Storage tank coverage with waterproof material

LCA and LCC as decision tools for defining sustainable rehabilitation and repair strategies

4

4.1 Introduction

Urban water systems are central infrastructures. These assets have been generally constructed and maintained over decades.

> "The circumstances that affect rehabilitation planning and prioritization include the current condition of the system, the extent of critical repair needs, the availability of funding for rehabilitation work, and the ability to inspect and assess the condition and deterioration rate of each element of the system." (EPA, 2009)

In addition to technical goals and objectives, the sustainable development of water supply and distribution infrastructure must increasingly be guided by planning approaches that "push back" the analytical boundaries to include the economic, environmental, and even social dimensions.

Arguably, the tightly linked nature of social institutions and infrastructure systems within industrialized societies (material production and manufacturing, transportation, energy and food production, water supply, rural and urban communities, and so on) mandates the development and use of holistic planning approaches to trace the interactions between these factors.

For example, systems planning and integrated approaches such as **life-cycle costing** (LCC) and **life-cycle assessment** (LCA) can be used to track life-cycle stage impacts of water supply infrastructure on biospheric and social networks (ISO ISO 14040: 2007).

Sustainability is becoming widely accepted as an important consideration for all projects related to urban water systems management.

Sustainable development is generally considered to have economic, environmental and social dimensions (Task Committee on Sustainability Criteria, 1998).

A number of measures have been suggested as being appropriate for assessing the various components of sustainability.

4.2 Life Cycle Cost

The most frequent method used to decide among various acceptable alternatives for the same project is a **direct cost comparison**. Results of such a restricted focus determination may be misleading since, the installed cost evaluation ignores many other costs which may occur during the lifetime of the sewer. **A true cost comparison must also consider the costs incurred (or avoided) throughout the design life** of the asset. The sum of all costs is called the Life Cycle Cost (LCC).

LCC analysis has entrenched itself firmly as a tool in the family of life-cycle thinking methodologies being applied the world over for projects, not limited to the built environment.

LCC has also forayed into brownfield and greenfield projects in the mining, manufacturing and power sectors of economies of the western world, and are gradually finding favour with the decision-makers and planners in the economies of the developing world. It goes without saying that investors, be they people from the industry or the government or the general public, are always eager to maximise their benefits while navigating the risky waters of rising costs and diminishing returns. Any project undertaken in the built environment in general would incur the following costs:

- Initial costs (material and land purchase, construction/installation, etc.)
- Fuel costs throughout the life cycle,
- Operation, maintenance and repair costs,
- Replacement and refurbishment costs,
- Disposal costs at end-of-life (and other Environmental costs if and when they are factored in),
- Loan interest payments.

The formulae used in the LCC calculation is based on standard formulae used in net present value calculations.

The basic formula for calculating the LCC is:

$$LCC = RC + PV_{RECURRING} - PV_{RESIDUAL\,VALUE}$$

where RC is the renewal cost at year 0, $PV_{RECURRING}$ (variable cost) is the present value of all recurring costs (maintenance, replacements, services), and $PV_{RESIDUAL\,VALUE}$ is the present value of the residual value after divestment.

Initial costs and the disposal costs at end-of-life are lumped at the two ends of the project life-cycle, while the others are recurring during the lifetime of the system built/maintained/used by the different entities in the project. These lumped costs would be one-off, while the recurring ones will be influenced by inflation. There are two types of maintenance activities, corrective maintenance (unplanned) and preventive maintenance (planned), respectively. **Preventive maintenance** is easy to include in LCC, corrective maintenance is hard to include in LCC. For urban water infrastructures, an example of preventive maintenance activities is scheduled cleaning/flushing of pipes. However, most maintenance operations on buried assets are of a **corrective nature** (after a failure occurs).

For a greenfield project, one could exercise control right at the concept design stage and plan to rein in costs and maximise benefits during a pre-defined lifetime. But, when one decides to apply LCC to an aging system, with the intention of optimising costs and improving level of service rendered to the customers, one can only use the past as history and attempt to decipher suboptimal patterns of expenditure, and the relation between improvement in performance and the costs incurred in the operation, maintenance and replacement operations in the past. A distinct pattern may or may not emerge and it would perhaps not be possible to find relationships in the past that could be extended into the future to make forecasts. In fact, this absence of a well-defined, explicable pattern will be the sore point.

When an LCC is done on an old system, what the analyst has is the capital stock value as a legacy from actions of the past, and a record of investments made, and expenses incurred in maintenance operations as a time series. This is where a methodology to decide upon how to split the budget available between investing big sums to improve the system and performing routine, less-expensive maintenance operations will come in handy.

While forecasting expenses and returns, studied assumptions would have to be made on the likely inflation rates and the discount rate. Profit-seeking firms would aim for a high Benefits/Costs ratio, but if one is studying the public utilities sector, it is often so that the government stresses more on welfare-maximising and operates at the break-even point. Hence, the aim is not to make profits and augment the benefits by doing an LCC, but to match the available funds with the required expenditure on providing the maximum level of service possible

LCC for infrastructure assets is challenging to conduct in an appropriate way because of the long-lived nature of the assets (80-150 years). The present value of cash flows far into the future gives a very small contribution to the LCC, and thus calculations spanning more than approx. 50 years into the future should be conducted with care.

Utilities are interested in the optimal time for replacement, i.e. when will the present value of continued maintenance exceed the present value of replacement (giving less maintenance).

Keeping an asset alive from year 0 to 1 is costly, keeping the same asset alive from year 100 to 101 is very cheap. This is because of the effect mentioned above, and the fact that generally assets are written off more aggressively than they deteriorate. In Europe, network assets are written off during 40 years, meaning they have no remaining book value (residual value) after this date. This is a great fault, as their service value generally remains high at this point. Assessing rehabilitation options using LCC makes little sense for utilities as long as this effect is not included in the calculation. It is "cheap" to replace an asset worth 0. It is more expensive to replace an asset that still carries between 60% and 90% of its initial value (because the utility then has to carry the loss of unused service potential).

LCC calculations currently only include direct costs. There are a number of other factors that should be included for the calculations to become credible (e.g. risk, reliability, social factors, consequential damages of works). Maintenance and renewal is not always conducted on the poorest pipes, but rather on the pipes that carries the greatest risk. If the consequence of failure is great, then the probability does not have to be great in order for the utility to consider action. Current LCC are only able to include probabilities, not costs of consequences (Ugarelli, 2010).

4.2.1 LCC method and supplementary measures

The **life-cycle cost** (**LCC**) is the total cost of owning, operating, maintaining, and (eventually) disposing of an asset over a given period of time (usually related to the life of the project) with all cost adjusted (discounted) to reflect the value of money. But the LCC of one asset has little value by itself. It is most useful when it can be compared to the LCC of other design alternatives which can perform the same function, in order to determine which alternative is most cost effective for this purpose. Those alternatives are called "mutually exclusive" alternatives because only one alternative for each system evaluated can typically be selected for implementation.

In calculating the LCC for a system, all future costs are generally discounted to their present – value equivalent (as of the base date) using the investor's minimum acceptable rate of return as the discount rate. However the LCC can also be estimated in annual value terms. An annual value is the cost resulting from amortizing all project costs evenly over the study period taking into account the time-value of money.

There are other measures of economic performance, as:

- Net Savings (NS)
- Savings-to-Investment Ratio (SIR)
- Adjusted Internal Rate of Return (AIRR),
- Simple Payback (SPB)
- Discounted Payback (DPB).

They are sometimes needed to meet specific regulatory requirements. All supplementary measures are relative measures, i.e., they are computed for an alternative relative to a base case. The supplementary measures of performances are based on the following criteria:

- **Net savings (NS):** The net savings (NS) is calculated as the difference between the present worth of the income generated by an investment and the amount invested. Or in other words operational savings less difference in capital investment costs. Preferred alternative has the maximum NS (> 0) for optimal cost effectiveness. The option with the highest NS will also have the lowest LCC.
- **Savings to Investment Ratio (SIR):** SIR is the ratio of the present worth of the income generated by the investment to the initial investment cost. Or in other words: the ratio of operational savings

to difference in capital investment costs. Preferred alternative should have the greatest SIR (> 0) for ranking projects.

- **Discounted payback period (DPP):** The payback period is the length of time until the sum of an investment's cash flows equals its cost. The payback period rule is to take a project if its payback period is less than some pre-specified cut-off. Or in other words: time required for the cumulative savings from an alternative to recover its initial investment cost and other accrued costs, taking into account the time value of money The discounted payback period (DPP) is the length of time until the sum of an investment's discounted cash flows equals its cost. The discounted payback period rule is to take an investment if the discounted payback is less than some pre-specified cut-off. It is recommended that it should only be used a screening device in LCC calculations and DPB should be less than study period. Simple Payback, is the time required for the cumulative savings from an alternative to recover its initial investment cost and other accrued costs, without taking into account the time value of money
- **Internal rate of return (IRR)** and adjusted Internal Rate of Return (AIRR): Internal rate of return (IRR) is the discount rate that makes the estimated Net Present Value (NPV) of an investment equal to zero. The IRR rule is to take a project when its IRR exceeds the required return. Adjusted internal rate of return (AIRR) is an annual yield from an alternative over the study period, taking into account reinvestment of interim returns at the discount rate. AIRR should be greater than discount rate and is used for ranking projects.

4.2.2 Step-by-step procedure to implement LCC

The variables to be included in applying LCC to a new asset or to an asset already operating are different.

When LCC is undertaken for a new project one could exercise control right at the concept design stage and plan to rein in costs and maximise benefits during a pre-defined lifetime. Different alternatives can be compared to choose the most cost-efficient solution; an example of LCC application at this stage is often performed to select pipe material best suited for service, with analysing different installation solutions and externalities that are additional to LCC but not mandatory.

When LCC is applied to an existing pipe the analysis often becomes a sustainability analysis. The pipe can be a very old asset that has lost its economic value, but still with adequate hydraulic and structural performances. The question is if it is worth to replace the pipe and, if not, when it could be more cost-efficient to invest on replacing it. The answer cannot only be based on a direct cost analysis between the historical O&M costs occurred on the asset, and regressed into the future, and the investment cost to replace it, including externalities. The analysis also has to take into account of a "risk cost" to include the expected costs for the asset that is aging and that has a certain risk of failing. The decision between maintaining the pipe or replacing it, is then not only driven by costs, but also by the pipe's performance that can be more or less acceptable regardless of the age of the asset and customer expectations.

The steps of a procedure for LCC are described in this paragraph, while in the followings a different discussion is presented for a new-pipe or an existing pipe project.

To perform LCC the following steps should be followed:

1. Define the analysis period of the project;
2. Define the service life of the alternatives;
3. Define the initial cost;
4. Identify future activities for each alternative and their timing throughout the project's life;
5. Compute maintenance, rehabilitation and replacement costs;
6. Compute residual value;
7. Estimate both utility and customer externality costs and include them in the activities for each alternative;
8. Discount future costs to present value;
9. Compute the Life Cycle Costs;
10. Compare the results for the alternatives.

Generally a project is cost-effective, if it has a LCC lower than the next best alternative.

To determine the most economical choice, the principals of economics must be applied through a life cycle cost analysis, so, in such analysis all factors affecting the cost effectiveness must be evaluated. The **factors** are:

- Project design life
- Asset expected life
- Initial cost
- Interest (discount rate)
- Inflation rate
- Maintenance cost
- Replacement cost (Investment)
- Depreciation rate
- Residual value

There are numerous costs associated with acquiring, operating, maintaining, and disposing as asset. Which of these costs needs to be included is one of the first decisions to take when performing a life-cycle cost analysis of alternative strategies. To answer the question, it is necessary to look at the economic effects that will result from each design alternative. It is not necessary to include all project-related costs in an LCC of project alternatives. Only those costs that are relevant to the decision, and significant in amount, are needed to make a valid investment decision.

There are various ways of classifying the cost components of an LCC, depending on what role they play in the mechanics of the methodology. The most important categories in LCC distinguish between investment- related and operational – maintenance costs; initial and future costs; and single costs and annually recurring costs.

Another relevant voice of cost are "non – monetary" benefit and costs, that are project – related effects for which you have no objective way of assigning a monetary value. Nevertheless, it should be considered significant the non-monetary effect on a final investment decision and it should be included in the project documentation.

4.2.3 LCC applied to an asset already operating

When LCC is applied to an aging system, decide about the different rehabilitation technologies to be employed, requires specific knowledge of an asset's condition.

Knowledge of system condition is essential to rationalize "what" to do and "where" to do it. To estimate "when" to replace an asset, the utility needs to gather a high level of knowledge in order to answer to the following questions:

1. What are the maintenance costs related to the asset?
2. What are the costs related to risk of failures?
3. What is the level of service provided? What will be the level of service in the future?

To estimate "how" the utility needs to answer to:

4. Would alternative solutions reduce to an acceptable level the risk of failures and produce any improvements in level of service above the upgrading target?
5. What are the alternative solutions and their costs?

Since the goal of predictive AM is to minimise life-cycle costs while meeting the performance targets, economic analysis is essential. The economic analysis requires the following information:

- cost of operating the system;
- cost of repairing one failure in the existing pipe;
- cost of the consequence of a failure in the existing pipe (i.e. damage due to flooding in basements);
- cost of replacing the existing pipe with a new one.

The decision has to be based on today situation and on future development of the system's performance. While the system ages, maintenance costs increase and the risk situation grows more serious. If information are not available to completely describe the asset and estimate the expected failures, the need of maintenance of different asset's class can be analysed by tracking the past maintenance costs over time. The relationship between costs and aging can be gathered by regression of past O&M costs related to average age of the assets and adjusted for the single asset considered.

However, the average demand of maintenance of one class does not reflect the risk of failure associated to a single specific pipe; that is why the total cost function at pipe level includes two main components: one component related to maintenance interventions and one component related to risk of failure.

The cost of risk is the product of the probability of the failure, expressed in occurrences per year, and the consequence of the failure, expressed in costs. The result is expressed as cost per year. According to the level of priority of each utility, the risk considered is not necessary risk of a structural failure, like a collapse, or operational failure, like flooding in basement, but it can also be the risk of reduced level of service under a given target, like overloaded wastewater treatment plants. The cost component related to risk is not necessarily an O&M type of costs. Risk expressed in monetary terms can be a social cost, or an environmental cost, depending on the point of view applied to compute the risk.

Once the utility is able to build a cost function that describes the evolution in time of O&M costs of the aging asset that has a certain probability of failing with a certain cost of the consequence of failure, then it is the moment to select alternatives replacement strategies to compare the costs to maintain the existing pipe with the replacement solutions. The alternative pipes for replacement should be first compared in order to select the most cost-efficient alternative as new project. At this stage of analysis it is possible to determine optimal pipe replacement year by comparing in time of the costs of maintaining an aging pipe and the cost of replacing it. The result can be obtained graphically by depicting those costs as function of time of replacement. The optimal year for replacement is the year in which the cost to maintain the asset are greater than the expensive to replace it or renew it. By using this approach there is really no difference between a capital and a maintenance decision. Once risk is considered, both are approached in exactly the same way.

4.2.4 Conclusion

LCC supports AM decision makers in choosing among different project alternatives. The LCC technique evaluates the present value to install and maintain alternative systems including planning, engineering, construction, maintenance, rehabilitation and replacement and cost deduction for any residual value at the end of the proposed project design life. The decision makers can then readily identify the alternative with the lowest total cost based on the present value of all initial and future costs. LCC should be done for all decisions related to infrastructure design, construction, operation, maintenance and rehabilitation alternatives.

The decision on cost-effectiveness of alternative solutions should be based not only on a pure economic analysis but also on the relative importance of other factors like the social and environmental impact of each solution, future maintenance costs and need for further rehabilitation.

When dealing with an existing-pipe project, the decision between capital or maintenance solutions, in addition to direct costs comparison, should include the costs related to projected future failures and risk of failures.

4.3 Life Cycle Analysis

LCA also known as life cycle analysis, ecobalance or cradle-to-grave-analysis, is an ISO 14040 normalized method which assesses the environmental impacts of a given product or service. A life cycle analysis implies a fair and holistic assessment of raw material production, manufacture, distribution, use, disposal and all transportations that are caused during or for the product existence.

LCA is a tool may be used to optimise the environmental performance of a single product (ecodesign) or to optimise the environmental performance of a company. Common categories of assessed damages are global warming, greenhouse gases, acidification, smog, ozone layer depletion, eutrophication, eco-toxicological and human toxicological pollutants, desertification, land-use, as well as depletion of minerals and fossil fuels.

Several variants of Life Cycle Assessment exist of which the following can be mentioned:

- **Cradle-to-grave** which assesses the LCA of a product or system from its manufacture through the use phase and to the disposal phase.
- **Cradle-to-gate** LCA evaluates only a partial product/system life cycle from manufacture to the factory gate, the usage and disposal are not included.
- **Cradle-to-cradle** is similar to cradle-to-grave assessment but here the disposal is a recycling process producing new product or material.
- **Life cycle energy analysis** (LCEA) accounts all energy inputs to a product including not only direct energy inputs during manufacture, but also all energy inputs required to produce components, materials and services needed for the manufacturing process.

4.3.1 LCA of pipes used in urban Water networks

The literature review of LCA's for pipes material mainly includes studies dealing with the calculation of the Embodied Energy. The basic factors that influence the embodied energy impact of piping systems can be summarized as follow, beside the specific results of individual studies:

- Pipe size - the bigger the pipe the more embodied energy.
- Amount of materials used – more materials, higher embodied energy.
- Pipes produced with significant recycled material – these materials usually have a lower overall embodied energy
- Materials with a low embodied energy coefficient - the lower the coefficient the lower the embodied energy.
- Piping systems, which are more durable and have a longer life expectancy - less repair and replacement leads to lower embodied energy over the life cycle of the system.
- Piping systems, which can last longer with appropriate maintenance - extending life, rather than replacing reduces embodied energy for that system over its life cycle.

The various piping systems considered in the several studies address some of these issues, however, it should be noted that they do not address the final issue that should be further developed.

4.3.2 LCA steps

FUNCTIONAL UNIT

LCA´s for comparison of products should be based on the function of the respective products. The results of comparisons can vary remarkably, if products cannot provide the complete function. On the other hand additional functions, which will be provided by a product, can hardly be regarded. Examples for that are aesthetic aspects or human health.

The main purpose of water service companies is the provision of water supply and sewerage services to residential, industrial, and commercial customers. On this account it is sensible to choose a functional unit that is related to the annual water flow throughout the system. In the water sector the default functional unit is metric such as 1 kℓ or 1 Mℓ of water at the quality specified for that particular process or 1 kg of pipe, or 1 m of pipes.

BOUNDARIES

The chosen boundaries determine which of the ecological relevant processes are included in the analysis – more processes included along the life cycle will result normally in a higher ecological pressure of the product system. Excluding of processes along the life-cycle, as it is done in some studies will underestimate the overall impacts of the system.

ENERGY –BOUNDARY

There are great differences in the calculation of emissions linked to energy consumption. In some cases the emissions from external energy supply are not included. This reduces the overall impacts associated with external energy use and, favours processes consuming external energy. In some cases the feedstock energy (the energy content of the raw material) is not included, which can lead to a decisive advantage for products with high energy content of the raw materials like PVC or wood, discriminating products without or with less input of this type of raw materials.

ENERGY MIX FOR ELECTRICAL ENERGY

The share of the different types of energy production determines the environmental emissions linked with the consumed energy. There are crucial differences in the emissions behind energy supply in the European countries, so use of a national or EU-mix has effects on the results.

LIFE TIME

The assumed life-time of the different pipe products varies a lot in the different studies. This has quite proportional effects on the results. A shorter life time leads to an equivalent higher impact per functional unit. The frequently used practice to exclude life-time in the investigation is an assumption of equal life time as well.

REGIONAL SITUATION

The assumed regional situation of the production site also has great effects on the results as the situation of energy supply, environmental standards and the transport distances vary for different countries. There is no effect on the comparison if European data are used for all materials. If special regional situations are taken, this might dominate the results, so that they reflect rather regional differences than materials differences, which are valid under those regional conditions only.

PRODUCTION

All raw materials and the respective production processes shall be included. Moreover the processes involved in the final disposal of the product shall be regarded.

TRANSPORT

The transportation at all life stages of the product system shall be included. This concerns the upstream (raw material chain), the product distribution as well as the downstream processes (product disposal). If the ecological effects of transportation are not included, long-distance transportation is favoured.

PIPE INSTALLATION

Installation of the pipes is considered in most studies to be equal for all materials. In fact this ignores the differences in the wall thickness and the weight of the pipe. Moreover the required preparation of the ground surface differs between the pipes to some extent, but there is no agreement in that respect. Taking all that into account the equal assumption seems to be unjustified. In Ugarelli et al. (2010) it is possible to find the estimation of energy requirements for the different techniques used in the specific case study for pipes installation.

USE

The importance of the use phase depends on the respective product. Environmental relevant aspects of the use phase of pipes are:

- Maintenance and cleaning
- Failures, leakage, exfiltration and infiltration

Especially the second issue is dominated by lack of clear and concise data, so these effects are only qualitatively mentioned in the studies, mostly with sensitivity analyses.

WASTE DISPOSAL

Ecological effects of the disposal of used products are strongly linked to the regional situation. The dominance of landfill or waste incineration in a country may lead to really different results. In some cases the waste disposal is not included, as pipes remain buried in ground, favouring products with high waste amounts or problems in waste treatment.

SENSITIVITY ANALYSES

Sensitivity analysis is any check of the effects of uncertain conditions on the results. It serves to estimate the magnitude of effects, where frequently assumptions are used to quantify effects. The key issues for the different LCAs in the water industry are presented in the review of the different applications. Sensitivity and uncertainty analyses are usually performed in order to determine the sensitivity of the results (i.e. the scores calculated per 1 kℓ of water or wastewater) to changes of input data. For the water sector such changes could be changes in the amount of energy used per 1 kℓ of water or wastewater.

IMPACT ASSESSMENT, VALUATION

The most important impact categories used in the literature, including the water industry, are as follows:

- Abiotic and biotic resource consumption
- Global warming potential
- Stratospheric ozone depletion potential
- Photochemical oxidant formation potential (sometimes called smog formation potential)

- Ecotoxicological impacts (aquatic and terrestrial)
- Human toxicological impacts
- Acidification potential
- Eutrophication potential
- Waste (sometimes a special category, hazardous waste, is defined)
- Work environment

At the end of the impact assessment a score is produced for each of the impact categories chosen. All the scores for a certain product, in this case 1 kℓ of water and wastewater (at a particular quality), give the environmental profile of the product and a basis for comparison.

The results of impact assessments are values for the environmental pressure for each of the impact class leading to an environmental profile of the product. Other methods focus on total aggregation of the single pressures listed in inventory to one (or some) index (indices).

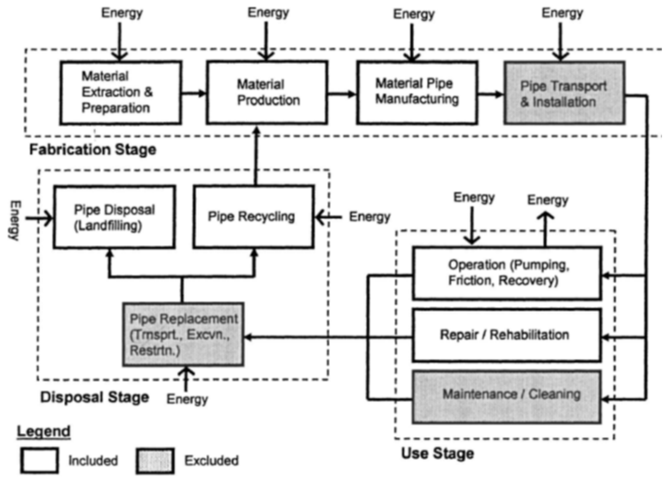
These methods mainly use factors of magnitude for the single pressures, which are created with completely different methods. Some are derived from expert panels, some come from willingness of public, some are tried to be based on physical background. In fact, all the methods for valuation have a considerable dominance of some pressures, which influences the results the more, the lower the number of dominant pressures and the more aggregated the results are.

According to ISO 14040 final aggregation to one index during valuation should not be performed.

SKETCHES FOR BOUNDARY CONDITIONS

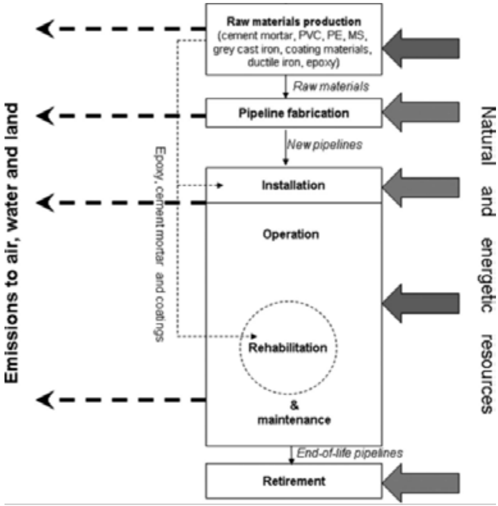
Different system boundaries can be found in literature for the urban water piping system used in the development of environmental sustainability indicators through LCA.

The system boundaries of the LCEA defined by Filion *et al.* (2004) are shown:

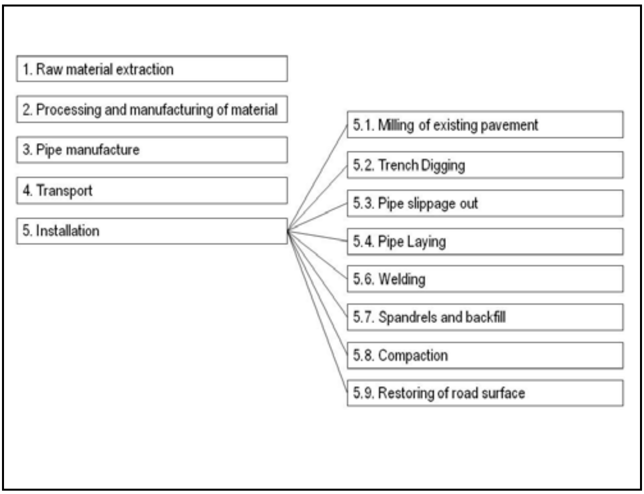


Life-cycle energy analysis boundaries and life stages (Filion *et al.*, 2004)

In Venkatesh *et al.* (2009) and Ugarelli *et al.* (2010) boundary conditions are mainly referred to the different phases of pipe life considered, even if, to be precise, the one presented should be used as sketches for data inventory and not for system boundaries.



Operating processes used in Venkatesh et al. (2009) for EE calculation



Operating processes used in Ugarelli et al. (2010) for EE calculation

4.3.3 LCA softwares and database

The software's used in the different studies reviewed are not specifically always mentioned. However, something can be said about the commercial models available for all type of LCAs studies and about the ongoing initiatives to developed databases.

Various European organizations have facilitated exchange of LCA information over the years (e.g., SETAC-Europe, LCANET, CHAINET, etc.). A first attempt to facilitate the exchange of LCI data was done by SPOLD (Society for the Promotion of Lifecycle Development), which worked to develop a common format for the exchange of life-cycle inventory data. In the beginning of this century the EcoSPOLD format was developed starting from SPOLD 99 and the ISO/TS 14048 data reporting format. Most commercially available LCA software programs (in particular CMLCA, EMIS, GaBi, KCL-eco, Regis, SimaPro, TEAM, and Umberto) are now able to import and partly even to export EcoSPOLD files. Most of the European databases that have been developed are only available through one of the many LCA software programs available (usually for a fee), with relatively few databases provided on a national, publicly available basis. However as for experience on our colleagues of the Environment and Architecture department the conversion of data between one software and the other is not always feasible (Kjersti Folvik, personal communication).

In its communication on Integrated Product Policy (http://ec.europa.eu/environment/ipp/), the European Commission concluded that Life Cycle Assessments provide the best framework for assessing the potential environmental impacts of products currently available. In the document, the need for more consistent data and consensus LCA methodologies was underlined. It was therefore announced that the Commission will provide a platform, called The

European Platform of Life Cycle Assessment, to facilitate communication and exchange of life-cycle data and launch a co-ordination initiative involving both ongoing data collection efforts in the EU and existing harmonization initiatives. The Platform provides quality assured, life cycle based information on core products and services as well as consensus methodologies (http://lct.jrc.ec.europa.eu/).

4.3.4 International Standards on LCA for pipes used in water networks

There is not specific standard to guide the application of LCA to the life circle of pipes as there is for instance to guide the calculation process for building sector with the ISO 21930:2007 " Sustainability in building construction – Environmental declaration of building products", and the coming European standard prEN 15804 - Sustainability of construction works – Environmental Product Declarations – core rules for the product category of construction products, and prEN 15978: "Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method".

The procedure that guides the LCAs found in literature, is the more generic ISO 14040 series.

In 1990, the Society for Environmental Toxicology and Chemistry (SETAC) initiated activities to define LCA and develop a general methodology for conducting the LCA studies. Soon afterwards, the International Organisation for Standardisation (ISO) (1997) started similar work on developing principles and guidelines on the LCA methodology. Although SETAC and ISO worked independently of each other, a general consensus on the methodological framework between the two bodies has started to emerge, with the difference being in the matter of detail only.

The International Organisation for Standardisation (ISO), provides guidelines for conducting an LCA within the series ISO 14040 and 14044 developed in 1997 and more recently reviewed.

The main phases of an LCA are:

- Goal & Scope definition: the product or service to be assessed is defined, a functional basis for comparison is chosen and the required level of detail is defined. (ISO14040 - ISO14041)
- Life Cycle Inventory (LCI): analysis of extractions and emissions. An inventory list of all the inputs and outputs of a product or service. (ISO14041)
- Life Cycle Impact assessment (LCIA): the effects of the resource use and emissions generated are grouped and quantified into a limited number of impact categories, which may then be weighted for importance. (ISO14042)
- Interpretation, the results are reported in the most informative way possible and the need and opportunities to reduce the impact of the product(s) or service(s) on the environment are systematically evaluated. (ISO14043)

In iso.org the reviewed versions are available as well and are:

- ISO 14040:2006. Environmental Management – Life Cycle Assessment – Principles and Framework
- ISO 14044:2006 - Environmental management -- Life cycle assessment -- Requirements and guidelines
- ISO/TR 14047:2003 Environmental management -- Life cycle impact assessment -- Examples of application of ISO 14042
- ISO/TS 14048:2002 Environmental management -- Life cycle assessment -- Data documentation format
- ISO/TR 14049:2000 Environmental management - Life cycle assessment - Examples of application of ISO 14041 to goal and scope definition and inventory analysis
- The interactions among the LCA phases are shown:

Interactions between LCA stages (from Fava et al. 1991).

The inventory list (LCI) is the result of all input and output environmental flows of a product system. However, a long list of substances is difficult to interpret, and this is why a further step is needed known as Life Cycle Impact Assessment (LCIA). An LCIA consists of four steps:

- Classification: all substances are sorted into classes according to the effect they have on the environment Life Cycle Inventory (LCI): analysis of extractions and emissions. An inventory list of all the inputs and outputs of a product or service. (ISO14041)
- Characterisation: all the substances are multiplied by a factor that reflects their relative contribution to the environmental impact
- Normalisation: the quantified impact is compared to a certain reference value, for example the average environmental impact of a European citizen in one year
- Weighting: different value choices are given to impact categories to generate a single score.

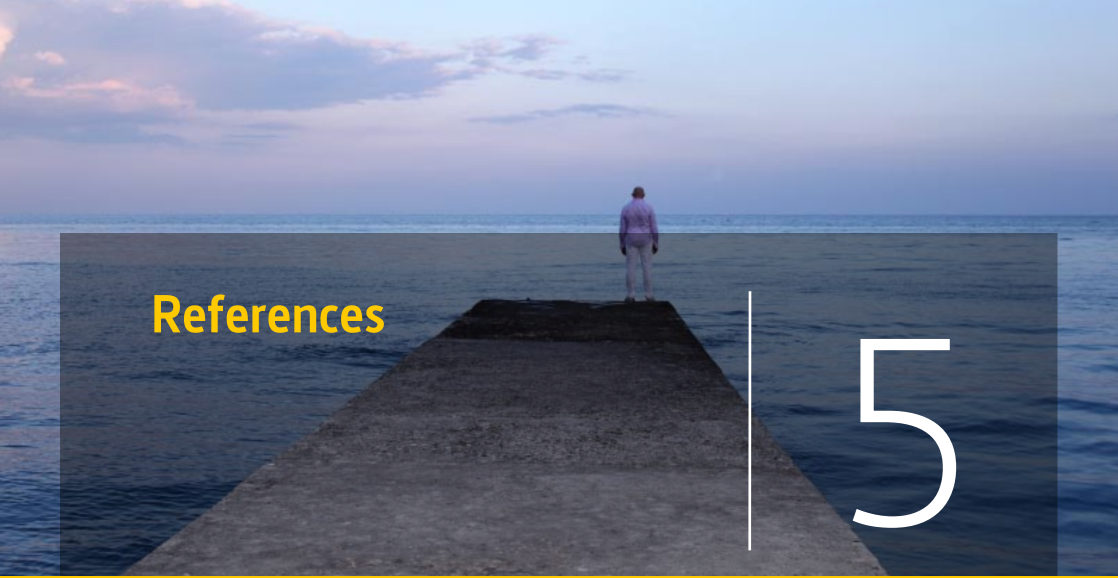
For each substance, a schematic cause response pathway needs to be developed that describes the environmental mechanism of the substance emitted. Along this environmental mechanism an impact category indicator result can be chosen either at the midpoint or endpoint level.

Midpoint impact category, or problem-oriented approach, translates impacts into environmental themes such as climate change, acidification, human toxicity, etc.

Endpoint impact category, also known as the damage-oriented approach, translates environmental impacts into issues of concern such as human health, natural environment, and natural resources. Endpoint results have a higher level of uncertainty compared to midpoint results but are easier to understand by decision makers.

4.3.5 Conclusion

The LCA studies can be applied at different levels in the water sector ranging from system level, process level or product level considering the entire life cycle of a product or process. LCA can be used as a tool both for basic research and for use in collaboration with the municipal and private partners. In fact, incorporating the life-cycle concepts into decision can help to make decisions about design and operations that can affect the environment. LCA can be used as a scientific tool to gather quantitative data to inventory, weigh, and rank the environmental burdens of products, processes, and services.



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D53.1d / MANUAL 5

Rehabilitation of water mains and storage tanks: technologies and decision support tools

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