AN ANALYSIS OF ROAD PAVEMENT COLLAPSES AND TRAFFIC SAFETY HAZARDS RESULTING FROM LEAKY SEWERS

Emilia Kuliczkowska

Faculty of Environmental, Geomatic and Energy Engineering, Kielce University of Technology,
Al. 1000-lecia Panstwa Polskiego 7, 25-314 Kielce, Poland
E-mail: emkulicz@tu.kielce.pl

Abstract. In this paper, road pavement collapses resulting from sewer leakage are divided into six categories: negligible, marginal, considerable, serious, very serious and catastrophic, with the categorization being based on two criteria, both related to traffic safety, i.e., the number of fatalities caused by sinkholes, and the extent of the road pavement damage. The causes of road pavement collapses are also discussed. The study involved analyzing the deterioration of sewer pipes with long service lives, focusing on the most common materials, i.e., concrete and vitrified clay. The results of the sewer inspections performed by the Kielce University of Technology suggest that the spot and linear defects detected in sewers of this type can be divided into three groups. The findings were used to formulate some recommendations on how to improve road traffic safety by preventing road pavement collapses.

Keywords: damage, road pavement collapse, sewer pipelines, traffic safety.

1. Introduction

Road traffic safety problems have been considered from different perspectives. The main emphasis, however, has been on road accidents. The rarely analysed factors affecting road traffic safety include road pavement failures caused by malfunctioning underground infrastructures, for example, a storm water drainage system, as described by Kalantari, Folkeson (2013). One of the reasons for road pavement subsidence or collapse is improper backfilling of the trench (Masada, Sargand 2007) when pipes are laid using the open cut method.

If pipes or culverts located below road pavements fail, they are likely to pose a serious threat to road traffic safety. Nowadays, sewers are frequently plastic pipes (Kuliczkowska, Gierczak 2013), or thin-wall steel liners (Ghorbani *et al.* 2013), which are likely to lose stability (buckling), causing road pavement subsidence and, consequently, its failure. Serious problems include excessive deflections of plastic pipes, for example, high-density polyethylene (HDPE) drainage pipelines used in highway projects in the US (Gassman *et al.* 2005). Recent investigations reveal that about 20% of the pipes inspected had deflections exceeding the 5% limit acceptable in North America. However, the greatest threats to road traffic safety are due to damaged vitrified-clay and concrete sewers with long service lives.

Some failures of underground infrastructures running under roads lead to the occurrence of large sinkholes, posing risk to road traffic safety. The most dangerous collapses of road pavements are reported to be due to failures of sewers, which are located deeper than any other underground service lines and are larger in cross-section. Road pavement collapses frequently swallow people and vehicles, with some of them ending in fatalities.

The literature-based analysis of over 100 cases of road pavement collapses due to damaged or leaky sewers, which occurred in different countries, shows that the collapses can be divided into six categories according to two different criteria. The causes of road pavement collapses were also investigated.

The scale of risk associated with road pavement collapses was determined using results of the closed-circuit television (CCTV) investigations performed by the Kielce University of Technology since 1991 to assess the condition of a total of more than 200 km of sewer pipes, (Kuliczkowska 2008), in different cities of Poland. The CCTV method involves inserting special cameras into sewers to video record their state (internal structural and operational defects).

This paper focuses on sewer defects responsible for road pavement collapses.

The results of the literature-based analysis and the CCTV inspections were used to formulate recommendations on how to prevent the occurrence of road pavement collapses.

2. Categories of road pavement collapses due to sewer defects

The categorization of road pavement collapses due to damaged or leaky sewers (Figs 1–2) is based on a study of over 100 recorded cases.

Two main criteria were considered:
– the number of deaths due to road pavement collapses;
– the extent of the road pavement damage.

Road pavement collapses are also classified according to the volume of subsidence or the cost of repair work, including the cost of reconstruction of collapsed buildings and road pavements, the cost of damage to vehicles, power cables, telecommunications cables, and water or sewer pipelines.

Table 1 presents the proposed categorization of road pavement collapses according to the number of fatalities, while Table 2 considers the extent of road pavement damage. Both include examples of failure.

3. Causes of road pavement collapses

Most sinkholes form naturally. They occur in locations where water, unable to flow laterally, percolates through soluble rock, creating caverns and cavities (especially in karst areas). Generally, they are not hazardous because they do not cause any depression in the land surface. If, however, the underground changes become too large, the outcome may be dramatic. Fortunately, cavity collapse type sinkholes form very rarely.

For example, in 2010 a serious failure was reported in the city of Guatemala, where an about 18 m sinkhole swallowed a whole intersection and a three-storey building.

The causes of road pavement collapses include failures of water mains. Pressurized water escaping from a damaged water pipe causes soil wash-out and, in consequence, soil subsidence. For instance, in Milwaukee in 2011, a water main break caused a sinkhole, which engulfed two cars. Similarly, in Toledo in 2014, a sinkhole resulting from a water main burst swallowed one car.

Road pavement collapses are mainly due to defects of sewer pipes resulting in leakage (e.g., sealing gasket intrusions and radial joint displacements), including structural defects (e.g., corrosion and cracks). Corrosion, abrasion or overloading are responsible for longitudinal cracking of pipes at the bottom and top and on the sides, where stress concentration is the highest (Fig. 3). The cracked pieces

Table 1. Categories of road pavement collapses, according to the number of fatalities

|	Failure category	Classification criterion	Example
1	Negligible	Small road pavement distresses in the form of cracks, linear rutting or local depressions, posing a threat to road users	Nisko, 1999; subsidence of road pavement along a length of 437 m with about 30 failure spots due to a leaky sewer below; local depressions with an area of 0.5–2.0 m^2 and a depth of several to a dozen cm
2	Marginal	Partly subsided road pavement; one vehicle swallowed into a small cave-in; no fatalities	San Francisco, 2012; approximately 6 m^2 subsidence of road pavement with a partly swallowed sewer-cleaning vehicle
3	Considerable	Large swallow hole, one or more vehicles swallowed, no casualties	Detroit, 2011; subsidence of road pavement (3.5 m × 7.6 m), sinkhole swallowing a vehicle with 2 women and a child, all saved by the event witnesses
4	Serious	1–2 deaths	Bryansk, 2012; subsidence of road pavement with an area of several m^2 swallowing a woman and a child, with the child killed
5	Very serious	3–10 deaths	Atlanta, 1993; road pavement subsidence; sinkhole about 24.4 m in diameter and 12.2 m in depth; 3 vehicles swallowed and 3 people dead
6	Catastrophic	More than 10 people killed	Guadalajara, 1992; explosion of sewer gases damaging 8 km of streets, killing 252 people (or approx 1000 people, according to unofficial reports), injuring about 1500 people, and damaging 505 vehicles

Fig. 1. Road pavement collapse with a swallowed bus

Fig. 2. Road pavement collapse with visible damaged cables and pipes

Table 2. Categories of road pavement collapses according to the extent of the road pavement damage

	Failure category	Area of road pavement collapse	Percentage of collapses in 100 randomly selected failures	Example
1	Negligible	No depression in road surface, small subsidence with slight road pavement distresses	0	Lack of published data on minor failures
2	Marginal	$F < 1\ m^2$	4	Kraków, 2012; $\Phi \approx 0.60\ m$ Vancouver, 2011; $\Phi \approx 0.46\ m$
3	Considerable	$1\ m^2 \leq F < 10\ m^2$	32	Mielec, 1995; $\Phi \approx 3 \times 3\ m$ Sydney, 2012; $\Phi \approx 1.5 \times 4\ m$
4	Serious	$10\ m^2 \leq F < 50\ m^2$	34	Changsha, 2012; $\Phi \approx 7\ m$ Montreal, 2013; $\Phi \approx 7.8 \times 4.8\ m$
5	Very serious	$50\ m^2 \leq F < 500\ m^2$	23	Lisbon, 2003; $\Phi \approx 10\ m$ Garwolin, 1995; $\Phi \approx 17 \times 5\ m$
6	Catastrophic	over $500\ m^2$	7	Seattle, 1957; $\Phi \approx 53 \times 61\ m$ Sterling Heights, 2004; $\Phi \approx 18 \times 49\ m$
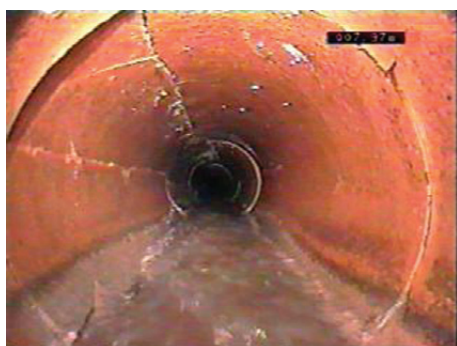
Fig. 3. Longitudinal cracks

Fig. 4. Vertical deformation of a cracked pipe

may break off (Fig. 4), which will eventually cause a sewer collapse (Fig. 5). Other hazards include displaced joints (Fig. 6) and missing wall pieces with air voids and soil visible beyond the defects (Fig. 7). Gradual subsidence of soil above a sewer leads to a road pavement collapse.

Infiltration of groundwater with soil particles into a sewer (Fig. 8) remains the greatest threat to road traffic safety. The scale of the phenomenon is assessed by determining the geometrical dimensions of leaky spots, the soil type (grain size), and the degree of soil compaction in the pipe zone. When infiltration of groundwater into a pipe occurs in a non-cohesive soil, finer soil particles are washed out until the leak is covered with coarser soil particles. This 'filter' can be damaged when the pipe operates under pressure, for instance, during heavy rainfall, as is the case of a storm water or combined drain. Storm water may then exfiltrate from a leaking pipe into the soil. When the rain stops and the flow of storm water in the pipeline decreases, groundwater with soil particles enters the pipe again causing the soil underneath to subside. The process results in the formation of air voids in the soil directly below the road pavement. These increase with time (Fig. 9), contributing to the subsidence or collapse of the road pavement. Such failures are generally less dangerous in non-cohesive soils than in cohesive soils, because air voids are smaller and the subsidence of the damaged road pavement

Fig. 5. Sewer collapse, an air void visible above the missing fragment of the sewer wall

is more shallow. The mechanism of infiltration and exfiltration in cohesive soils is identical to that in non-cohesive soil. The difference lies in that in cohesive soils air voids form directly above the damaged sewer (Figs 5, 10). The
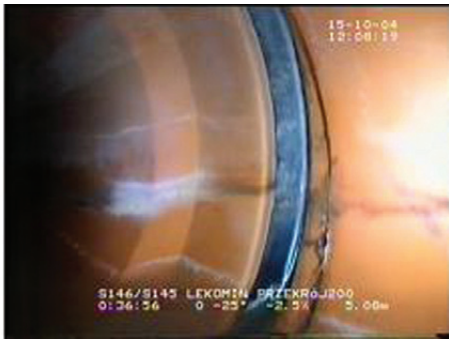
Fig. 6. Longitudinally displaced joint with a visible gasket

Fig. 7. Defective connection with visible air voids beyond the sewer wall
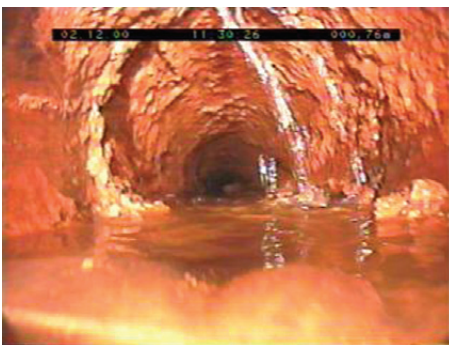

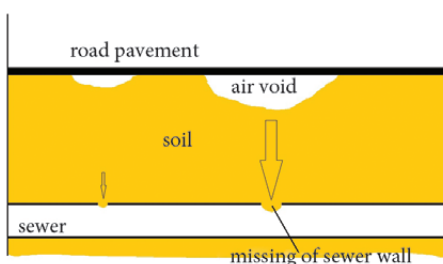**Fig. 8.** Infiltration of groundwater into the sewer

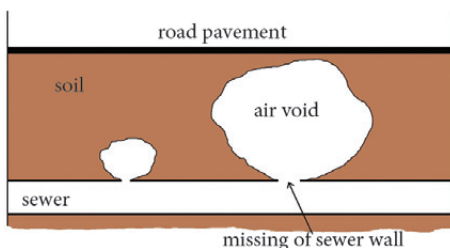**Fig. 9.** Air voids above a leaky sewer in a non-cohesive soil

Fig. 10. Air voids above a leaky sewer in a cohesive soil

formation of air voids in cohesive soils until they reach the lower layer of the road pavement usually takes from over a dozen to several dozen years. The sinkhole in Seattle in 1957, which was about 30 m wide, 40 m long and 45 m deep, occurred due to a collapse of the sewer main 44 years after its installation. The cave-in swallowed two parallel roads with a green strip in between. The sewer, laid in a cohesive soil, had been leaking from the very beginning. Collapses of road pavements occur sooner when pipes are laid at shallow depths or in non-cohesive soils.

Unlike the other types, catastrophic failures occur as a result of explosions of gases originating from the infiltration of industrial fluids into sewers.

4. Investigations concerning sewer deterioration

As deterioration is one of the fundamental causes of sewer failure, much of the current research focuses on developing sewer deterioration models. There is a wide variety of models to predict deterioration processes in pipelines, for instance, that of Scheidegger (2011). The models are categorised into three groups:

– polynomial;
– artificial intelligence;
– stochastic or probabilistic.

Because of the general lack of suitable data sets, Scheidegger *et al.* (2011) overviewed 49 papers, concluding that sewer system condition models are rarely validated. Structural deterioration of sewers pipelines has also been modelled outside Europe, for example, in the US (Younis, Knight 2010a), or Australia (Tran *et al.* 2008).

In many countries, sewer pipes are generally made of concrete, reinforced concrete or vitrified clay. According to Berger and Falk (2011), 42% of the sewer pipes in service in Germany are concrete pipes; the percentage of vitrified clay pipes is the same. From the analysis by Younis, Knight (2010a, 2010b), it is apparent that the deterioration of reinforced concrete pipes is age related. Such pipes are prone to corrosion caused by hydrogen sulphide, moisture or other reactive agents present in domestic sewage. Younis, Knight (2010a, 2010b) also demonstrate that the deterioration of vitrified clay pipes is age independent provided that the pipes are properly designed and installed, with no damage during installation.

From the above studies as well as inspections conducted in Poland, (Kuliczkowska 2008), it is evident that vitrified clay sewer pipes do not deteriorate with age. However, road pavements above such pipes may fail. The existing models for predicting deterioration of sewers are reported to be completely suitable for the analysis of concrete pipes, and completely useless for studying non-aging vitrified clay pipes.

Apart from deterioration of sewers, there are other factors contributing to sewer leakage and, eventually, to road pavement collapses. The most important are the defects arising from design, construction or maintenance errors. Road pavement collapses are also be due to the unsealing of joints (aging and cracking of sealing materials). Formerly, sewer pipes were joined using bitumen-dipped hemp and cement

mortar, clay or asphalt. With time, the materials deteriorate and fail to prevent infiltration of groundwater into the sewer or exfiltration of wastewater into the soil.

5. CCTV inspections as a method for sewer condition assessment

Field investigations of sewer pipes (Kuliczkowski *et al.* 2011; Madryas *et al.* 2012), enable accurate evaluation of their structural integrity. The condition of an excavated pipe is assessed by first measuring the thickness of the pipe wall (free from dirt, rust and other foreign material), then determining the strength parameters of the pipe material, the parameters of the surrounding soil, and the type of bedding, and, finally, performing static calculations to establish the safety factor of the sewer pipe.

Field investigations are necessary when there has been a substantial change in the loads acting on a pipe or when the consequences of a potential failure are serious. In large cities, where some sewer pipelines are hundreds of kilometres long, CCTV has become the most common method (Madryas *et al.* 2010; Stein 1999), to provide information about their condition. Special cameras are inserted into sewers to video record their state.

The inspections conducted by the Kielce University of Technology have covered more than 200 km of sewer pipes made of various materials, including concrete, reinforced or prestressed concrete, vitrified clay, asbestos cement, steel, cast iron, polyvinyl chloride (PVC), polyethylene (PE), polypropylene (PP), and glass reinforced plastics (GRP). This paper focuses on vitrified clay and concrete (reinforced concrete) sewers with long service lives. It summarizes the analysis of 14 897.1 m of vitrified clay sewer pipes randomly selected in 19 Polish cities. Sixty six inspections were conducted, and they were diverse in terms of town, street and pipe diameter. 422 sections of pipelines were inspected, with diameters ranging from 200 mm to 500 mm. The analysis also covered concrete sewers with a total length of Seventy inspections 14 116.5 m randomly selected in 21 Polish cites. Seventy inspections were conducted for different towns, streets and pipe diameters. 404 sections were inspected. The sewer pipes varied in diameter, ranging from 200 mm to 800 mm.

The main aims of CCTV inspections are:
− identification of leakage and defects that are likely to result in leakage;
− quantitative analysis of these defects.

The following defects were analysed:
L01 – groundwater infiltration into a leaky sewer,
L02 – post infiltration encrustation,
L03 – sealing gasket intrusion,
L04 – missing wall pieces,
L05 – sewer deformation or collapse of a cracked rigid sewer,
L06 – root intrusion,
L07 – longitudinal cracks,
L08 – circumferential cracks,
L09 – diagonal cracks,
L10 – defective connection,
L11 – pipe intrusion,

L12 – radial joint displacement,
L13 – longitudinal joint displacement,
L14 – abrasion of the pipe bottom,
L15 – internal corrosion.

Sewer defects identified through CCTV investigations are divided into two main groups:

a) spot defects (L01, L02, L03, L04, L06, L08, L09, L10, L11, L12, and L13) in number per 100 m,

b) linear defects (L05, L07, L14, and L15), in percentage, determining the ratio of the length with defects to the total length of the sewer.

It is also possible to classify the effects as:

A. defects that confirm the loss of leak tightness (L01, L02, L03, L04, and L05);

B. defects that exhibit a risk of leakage (L06, L07, L08, L09, L10, L11, L12, and L13); for example, a crack is observed over a part of the sewer wall thickness, with the pipe being leak tight, or across the whole wall thickness, with the pipe being leaky;

C. defects that may eventually cause cracks of pipes and a loss of their leak tightness (L14, L15).

6. Results of the CCTV inspections for sewer pipes with long service lives

The CCTV inspections were performed for concrete and vitrified clay sewer pipes with long service lives. Figs 11 and 12 show defects posing a threat to road surface integrity, which are spot and linear defects, respectively.

In vitrified clay pipes, the most frequent spot defects responsible for the loss of leak tightness are radial joint
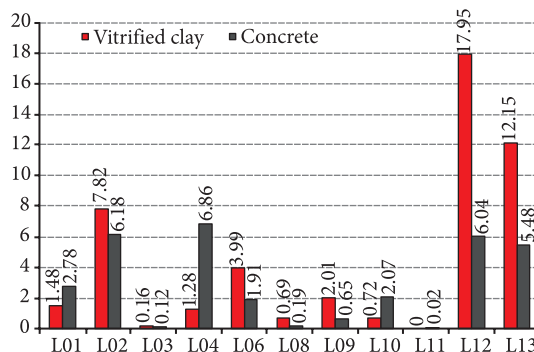
Fig. 11. Frequency of spot defects in vitrified clay and concrete sewers, in number per 100 m
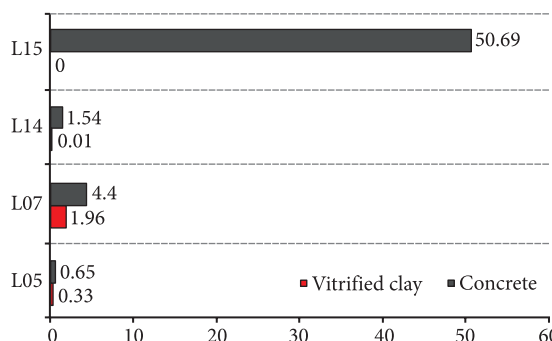
Fig. 12. Summary of linear defects in vitrified clay and concrete sewers, in percentage

displacements L12 (17.95 defects/100 m), while the most common linear defects are longitudinal cracks L07, observed along 1.96% of the pipe length. Defects classified as group A, posing the greatest threat to road surface integrity, comprise:

- infiltration of groundwater into a leaky sewer (L01), with 1.48 defects/100 m;
- post infiltration encrustation (L02), with 7.82 defects/100 m;
- sealing gasket intrusions(L03), with 0.16 defects/100 m;
- missing wall pieces (L04), with 1.28 defects/100 m;
- deformation or collapse of a cracked rigid sewer (L05), 0.33%.

In concrete pipes, the predominant linear defect contributing to a loss of leak tightness is internal corrosion (L15), occurring along 50.69% of the length of the pipes studied. The major causes of spot defects, on the other hand, are post-infiltration encrustation (L02), with 6.18 defects/100 m, missing wall pieces (L04), with 6.86 defects/100 m, radial joint displacements (L12), with 6.04 defects/100 m, and longitudinal joint displacement (L13), with 5.48 defects/100 m. The first and second of the spot defects are group A defects, i.e., ones posing the greatest threat to road surface integrity. This group also includes:

- infiltration of groundwater into a leaky sewer (L01), with 2.78 defects/100 m;
- sealing gasket intrusions(L03), with 0.12 defects/100 m;
- deformation or collapse of a cracked rigid sewer (L05), 0.65%.

The results show that sewers with long service lives contain a large number of defects that are likely to result in a road pavement collapse and pose a threat to traffic safety.

7. Methods of prevention of road pavement collapses

The basic method used for sewer condition assessment is the CCTV method (Hao *et al*. 2012). CCTV inspections need to be performed periodically. However, if a CCTV footage provides no information about defects, it does not mean that the sewer is leak tight or that phenomena posing a threat to road surface integrity, as described in Section 3, do not occur in the surrounding soil. For instance, when the groundwater level is below the sewer bottom, it is impossible to assess whether or not the pipe joints are leak tight by applying only the CCTV method. In this case, the possible phenomena include exfiltration of sewage into the soil around pipes (unnoticeable during a CCTV inspection) or wash-out of soil with groundwater originating from storm water to the inside of the sewer. These phenomena pose no direct threat to sewer integrity. However, because of soil destabilization around sewers, they pose a serious threat to road traffic safety.

Companies maintaining road pavements and those responsible for road traffic safety are expected to be interested in expanding the scope of investigations related to:

a) checks for leaks in sewer pipes, which involve the use of high-pressure air or water, or use of the electro-scanning method (Hansen 2014);

b) checks for air voids in the soil around sewers by conducting in-sewer ground penetrating radar inspections (Ekes *et al*. 2014).

If leaks or air voids posing risk to traffic safety are detected, the faulty sewer pipe needs to be replaced, using open cut methods, or renewed (Kuliczkowski *et al*. 2010; Stein 1999), by applying one of the trenchless methods, and these fall into six categories: sealing (e.g. the Penetryn, Posatryn, Seal-i-Tryn, Weco or Amex methods), repair (e.g. the Point-Liner, Quick Lock, Snap-Lock, and Link-Pipe systems as well as various repair robots), replacement (e.g. static, hydraulic or pneumatic Berstlining, Hydros or Pipe Replacer), non-structural rehabilitation (cement or polyurethane spray-on lining, thin-walled HDPE, PP, PVC or GRP lining, Rib Loc, Trolining and non-structural CIPP – cured in place pipe methods), semi-structural rehabilitation (semi-structural CIPP methods, short or long Relining using semi-structural HDPE, PVC, PP, GRP or other pipes) and fully structural rehabilitation (fully structural CIPP methods, short or long Relining using fully structural HDPE, PVC, PP, GRP or other pipes). For some materials, trenchless technology is able to ensure leak tightness and integrity of sewers, and, in consequence, good condition of road pavements and road traffic safety for more than 50 years.

8. Conclusions

1. This paper has examined 100 road pavement collapses caused by sewer defects that have occurred in different countries. The results suggest that there are six categories of road pavement collapses: negligible, marginal, considerable, serious, very serious and catastrophic. The categorisation is based on two criteria related to road traffic safety:

- the number of people killed (and vehicles damaged); the largest of the disasters reported 252 people dead and 505 vehicles damaged, although, according to unofficial records, the death toll reached about 1000; in many events, fatalities ranged from one to several people; in the majority of cases of vehicle damage, the drivers and occupants were only injured;
- the extent of the road pavement damage; the average surface area of a collapse is 49.43 m^2; the biggest failure damaged 8 km of roads; the smallest collapse analysed, had a surface area of 0.12 m^2.

2. The analysis points to several causes of road pavement collapses. Natural collapses generally occur in limestone karst areas. The other reasons include leaky water mains, leaky storm sewers and leaky sanitary sewers. The most serious collapses are those caused by leakage from a sanitary sewer system because sewer pipes are bigger in diameter and placed at greater depths than water mains.

3. It has been found that the depth and volume of sinkholes are dependent mainly on the type of soil above the sewer. Road pavement collapses are generally:
- deep in cohesive soils because of large air voids forming above leaky sewer pipes;
- shallow in non-cohesive soils, where air voids form directly below the road pavement.

4. The investigations focused on road pavement collapses due to sewer defects. The results point to two major causes:
- leakage of sewers, which frequently result from installation errors (e.g., installation of pipes damaged during transport or assembly), design errors (e.g., selection of improper joints or gaskets), with these errors being rare, and, finally, operational errors (e.g., transport of sewage failing to meet the standard requirements);
- deterioration of sewers (e.g., corrosion or abrasion of concrete sewers) or their overloading, which will result in cracking, vertical deformation of the cracked pipe, and, finally, a total collapse.

5. The results of the sewer inspections performed by the Kielce University of Technology indicate that there are 15 types of sewer defects associated with leakage or possibility of leakage occurrence. These are: infiltration of groundwater into a leaky sewer, post infiltration encrustation, sealing gasket intrusions, missing wall pieces, deformation or collapse of a cracked rigid sewer, root intrusions, longitudinal cracks, circumferential cracks, diagonal cracks, defective connection, other external factors affecting the state of a sewer wall, radial joint displacements, longitudinal joint displacements, abrasion of the pipe bottom, and internal corrosion. All these defects pose a threat to road traffic safety.

6. The quantitative analysis of defects in the sewers inspected by the Kielce University of Technology shows that, in the case of vitrified clay sewer pipes, the most frequent defects posing risk to the safety of road traffic are: infiltration of groundwater into a leaky sewer (1.48 defects/100 m), post infiltration encrustation (7.82 defects/100 m), sealing gasket intrusions(0.16 defects/100 m), missing wall pieces (1.28 defects/100 m), and deformation or collapse of a cracked rigid sewer (0.33%). For concrete sewers, the most common defects posing risk to traffic safety are: post infiltration encrustation (6.18 defects/100 m), missing wall pieces (6.86 defects/100 m), infiltration of groundwater into a leaky sewer (2.78 defects/100 m), sealing gasket intrusions (0.12 defects/100 m), and deformation or collapse of a cracked rigid sewer (0.65%).

7. From the experience in the management of sewer systems, it is clear that periodic inspections of sewer pipelines are necessary. However, sewer inspections carried out by maintenance teams are insufficient. It is recommended that they be supplemented by leak tightness tests as well as surveys of the soil around sewers performed by means of in-sewer ground penetrating radars.

8. Sewers posing a threat to road traffic safety need to be replaced, using open cut methods, or renewed, by applying trenchless technologies (sealing, repair, replacement, and non-structural, semi-structural or fully structural rehabilitation), which will cause no or minimal disruption to road traffic.

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