

## Evaluation of testing procedures for real-scale sewage pipes

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### ABSTRACT

Tests to determine the tightness of wastewater pipes can in some cases produce results that are worthy of discussion. Therefore, testing procedures for real-scale sewage pipes used for house connections were evaluated and data were statistically analysed. The results of the investigation showed that leaky pipes are detected with a very high degree of reliability by all leak test methods. The test methods are also robust against errors by expert testers and deviations from the test specifications. In contrast, tight pipelines can also be incorrectly classified as 'leaking' (test failed) to a significant extent during leak tests. Even for the more reliable test methods, i.e. air overpressure, air underpressure and water with low test pressure, a tight pipe is incorrectly classified as leaking (false positive) in one out of 10 cases (10%). The highest false-positive rate was 20% for water with high test pressure. In addition to the leak test methods, the quality of the visual inspection was also analysed. Here it was found that visual inspection is not sufficiently reliable for determining the tightness of pipelines above the groundwater level. Error rates of approximately 50% were found for the detection of tight and leaky pipelines.

**Key words:** inspection, leak test, pipelines, quality, sewerage, wastewater

### HIGHLIGHTS

- Investigation of the quality of leak tests and visual inspection for sewage pipes on a real scale.
- Determination of error rates for the different test methods (visual inspection, air overpressure, air underpressure and water pressure).
- Evaluation of the different test methods for the determination of tightness.
- Development of recommendations for action to increase the reliability of the test results.

### INTRODUCTION

In addition to stability and operational safety, tightness is the permanent functional aim of wastewater pipes. Therefore, according to § 61 'Self-monitoring for wastewater discharges and wastewater facilities' of the German Water Resources Act (WHG) (2009), the operators of wastewater systems are obliged to monitor the condition and functionality of their systems themselves. If monitoring is not carried out, pipe damage may remain undetected and groundwater may enter the sewer system (infiltration) or wastewater may escape (exfiltration), with consequences for the environment. Various test methods are available for checking the tightness of connection pipelines: The simplified leak test with water or air according to DIN 1986-30 (2012) for existing pipes, the leak test with water or air according to DIN EN 1610 (2015) for newly constructed or renewed pipes and the visual inspection according to DIN 1986-30 (2012). The leak tests are carried out by expert testers in accordance with the above-mentioned procedures. The tests are assessed as 'passed' or 'failed' depending on specific limit values for the respective procedures with regard to the criterion 'leak tightness'.

In Bosseler *et al.* (2018), the leak tests and visual inspections carried out on rehabilitated sewage pipes used in house connections showed results that were worthy of discussion. On the one hand, despite passing the leak test, leaky areas could definitely be detected during the subsequent visual inspection using camera technology under external water pressure. On the other hand, pipes that exceeded the permissible water addition by a multiple during the leak test did not show any obvious infiltrations during the visual inspection under external water pressure. Thus, the quality of the leak tests and visual inspection in these cases is more than questionable.

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The fact that incorrect test results can be obtained when carrying out tests was further confirmed by expert interviews with sewer network operators, test equipment manufacturers, pipe manufacturers, construction companies and training institutions for obtaining expertise in condition and function testing ('expert tester') (Ulutaş 2017). Consequently, 'tight pipes' can be tested as 'test failed' (false positive) and 'leaky pipes' as 'test passed' (false negative).

The topics of 'leak testing' and 'visual inspection' in drainage networks have already been addressed in numerous research projects and scientific papers. Schwebel (1989) developed an air pressure test method for checking the tightness of wastewater pipes. Proof of the correlation between the water pressure and air pressure test was provided by Kaufmann (1997). Künster (2002) developed test criteria for leak testing of individual pipe joints in sewers that cannot be walked inside. In addition, the organisational implementation of leak tests for wastewater pipes was investigated (Pinnekamp *et al.* 2005). An overview of the methods available on the market for condition assessment and leakage testing of house connection pipes is given in Bosseler *et al.* (2003). The uncertainties due to a subjective assessment of an inspector in the condition detection (damage detection and classification) of wastewater pipes by means of visual inspections were investigated by Dirksen *et al.* (2011), Sousa *et al.* (2014) and Caradot *et al.* (2017). Furthermore, Roghani *et al.* (2019) determined the influence of uncertainties in condition assessment with a prediction model. Van der Steen *et al.* (2013) investigated the influence of the coding system on the quality of the inspection data.

However, there are currently no well-founded scientific studies on the quality of leak tests and visual inspections for determining the tightness of wastewater pipes used in house connection on a broad data basis. In addition, there is a lack of reliable data on the quality of the tests and on error rates and their effects. There are also no statistically validated findings on which factors can influence the quality of the test results.

The aim of the study was to determine the quality of the various test methods for leak tests (water pressure, air overpressure and air underpressure) and visual inspection of connection pipelines for the first time on the basis of empirical investigations. The investigations on rehabilitated pipes were carried out in a large-scale test stand on a real scale under practical conditions. Here, test results from the expert testers were compared with the actual pipeline conditions in order to determine the respective error rate for the individual test procedures. The sensitivity and specificity of the test methods investigated were determined and, based on this, the correct classification rate assessed. Finally, on the basis of the results obtained, specific recommendations for action were developed to make the testing more reliable. This included information on the quality of the test results and on the areas of application of the different test methods.

## MATERIALS AND METHODS

Investigations took place in the large-scale test stand with the dimensions  $w \times h \times l = 6 \times 6 \times 15$  m.

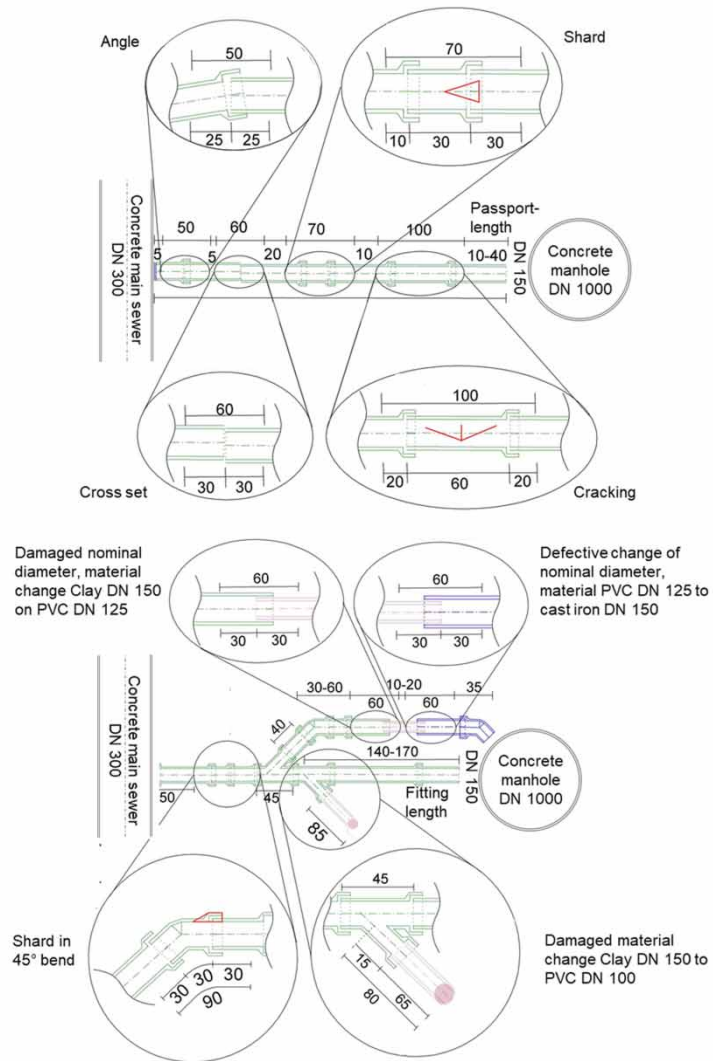
The test set-up included a total of 10 set-ups with 28 pipelines (10× lower pipelines, 18× upper pipelines, Figure 1) with damage patterns that were rehabilitated after installation using different rehabilitation methods. In the lower layer, three different pipe runs were installed for the use of short liners (8×), side connection profiles (1×) and inner collars (1×). In the upper layer, two pipelines (16×) were installed for repair using short liners and one pipeline (2×) was installed per structure for renovation using CIPP liners.

The rehabilitated pipelines were then subjected to various loads. Based on this, the examination procedure for checking the quality of the leak tests and visual inspections were carried out. A test set-up from the research project (Bosseler *et al.* 2018) was used for the investigations.

In total, 980 individual tests were carried out by seven expert testers on the test sections in the large-scale test stand. The expert testers had to prove their expertise in leak tests and visual inspections in order to carry out the tests. The proof includes a training course of at least 3 days in accordance with the state requirements and an examination to obtain the expertise. In addition, the expert inspectors had the following professional qualifications: 1× civil engineer (urban water management), 2× qualified employee (sewer operation) and 4× foreman (2× road construction, masonry, sanitation).

Each of the seven experts carried out the following tests on the 28 pipelines:

- Visual inspection using camera technology according to DIN 1986-30
- Air overpressure test (DIN EN 1610: test pressure: 100 mbar and test time 3 minutes)
- Air negative pressure test (DWA-A 139: test pressure: -100 mbar and test time 2.5 minutes)
- Low-pressure water test (DIN 1986-30: test pressure: 50 mbar and test time 15 minutes)
- High-pressure water test (DIN EN 1610: test pressure: 200 mbar and test time 30 minutes)



**Figure 1** | Sample test set-up for short liner (top) and sketch of lower pipeline (middle) and upper pipelines (bottom) each with dimensions.

In order to be able to analyse the test results of the seven expert testers with regard to test errors, the actual pipe condition was first determined for the 28 pipelines. To determine the condition of the pipelines, independent control measurements were carried out in the form of eight visual tests under external water pressure load and water pressure test according to DIN EN 1610 (test pressure: 500 mbar and test time 30 minutes) on exposed pipelines (Figure 2).

Finally, the results of the control measurements (eight visual inspections under external water pressure and the water pressure test after exposure of the pipelines) were evaluated and the following categories for the actual pipe conditions were determined (Figure 3):

- Pipeline condition 'Leaky – water surge/flow'
- Pipeline condition 'Leaky – drips'
- Pipeline condition 'Tight'

As a result, the condition of 25 of the 28 pipelines could be clearly determined. For three pipes, the pipe condition could not be determined unambiguously, as moisture and drip formation were observed at the rehabilitated damaged areas in the course of the water pressure tests. These could also result from residual moisture in the annular space between the old pipe and the short liner (individual case: liner without adhesive bond) (Bosseler & Ulutaş 2018).

Subsequently, the results of the expert testers were compared with the actual pipe conditions in order to determine the false-negative rate and the false-positive rate for the individual test methods on this basis. In order to gain further insights into the quality of leak tests, all test results were first standardised to improve comparability and then analysed and evaluated.

The visual inspection procedure was used to determine which abnormalities that could lead to infiltration could be detected even without external water pressure. For this purpose, the seven expert testers were asked after completion of the respective visual inspection of the pipelines whether they assessed the pipe condition as 'tight' or 'leaky'. The inspectors' assessments were then compared with the actual conditions determined (control measurement). The evaluation was carried out depending on the three different pipeline conditions 'Leaky – water surge (WS)/flow (F)', 'Leaky – drips (L)' and 'Tight (T)'.

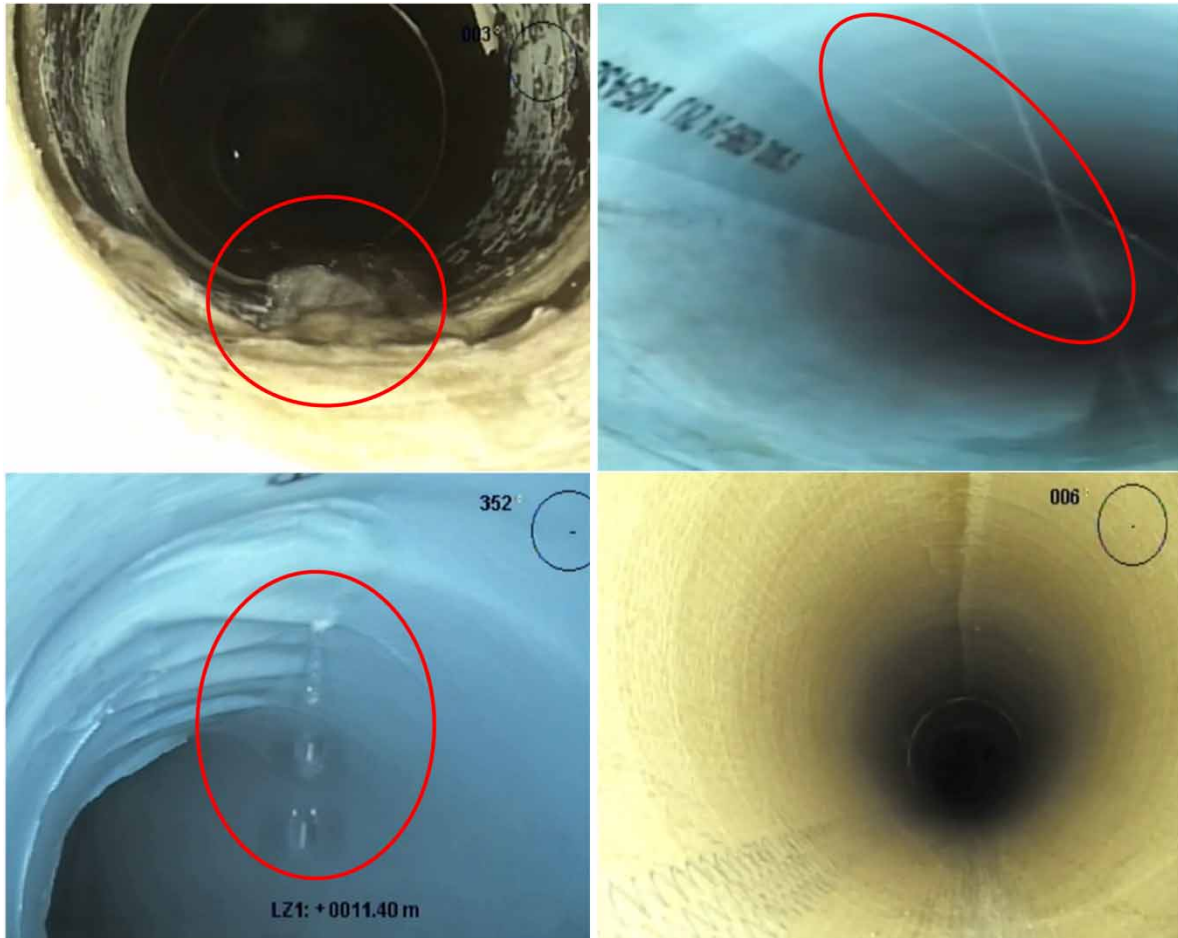
## RESULTS AND DISCUSSION

The test results of all leak test procedures for the pipeline condition 'Leaky – water surge/flow' show that 307 out of 308 individual tests (true-positive rate of 99.7%) were evaluated as failed (leaking) by the expert testers. Only one individual test was incorrectly rated as passed (false negative) in the air-vacuum test (Figure 4). The test results of all leak test procedures for the pipe condition 'tight' show that 195 of 224 individual tests (true-negative rate of 87%) were evaluated as passed (tight) by the expert testers. In total, 29 individual tests (6× positive air pressure/ negative air pressure, 12× water at high pressure and 5× at low pressure) distributed over the different test methods were incorrectly evaluated as failed (false positive) by the expert testers (Figure 5).

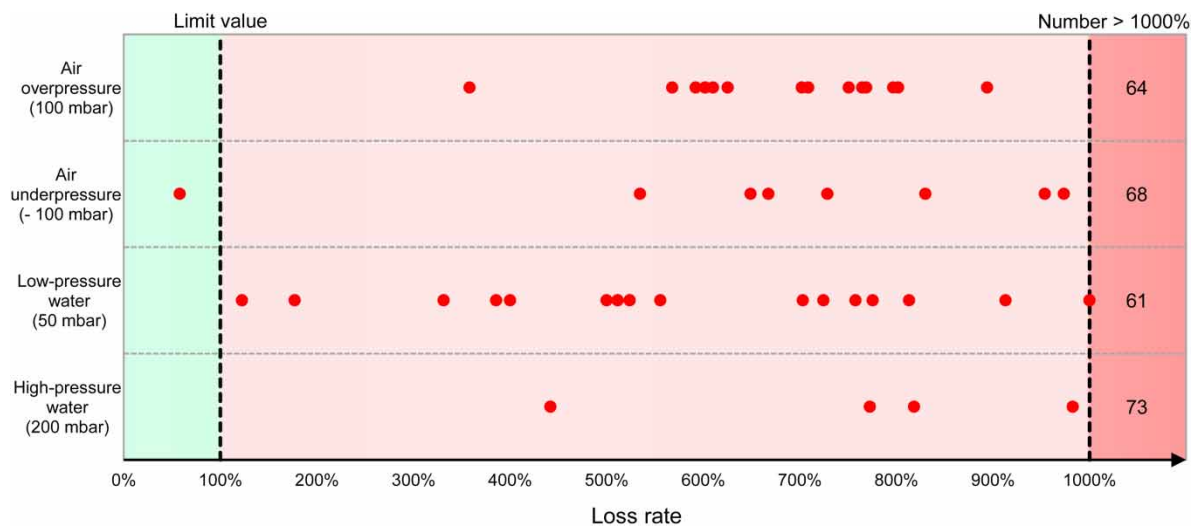


**Figure 2** | Carrying out the visual inspection in the covered state under external water pressure (left) and carrying out the internal water pressure tests with inspection from the outside on exposed pipelines (right).

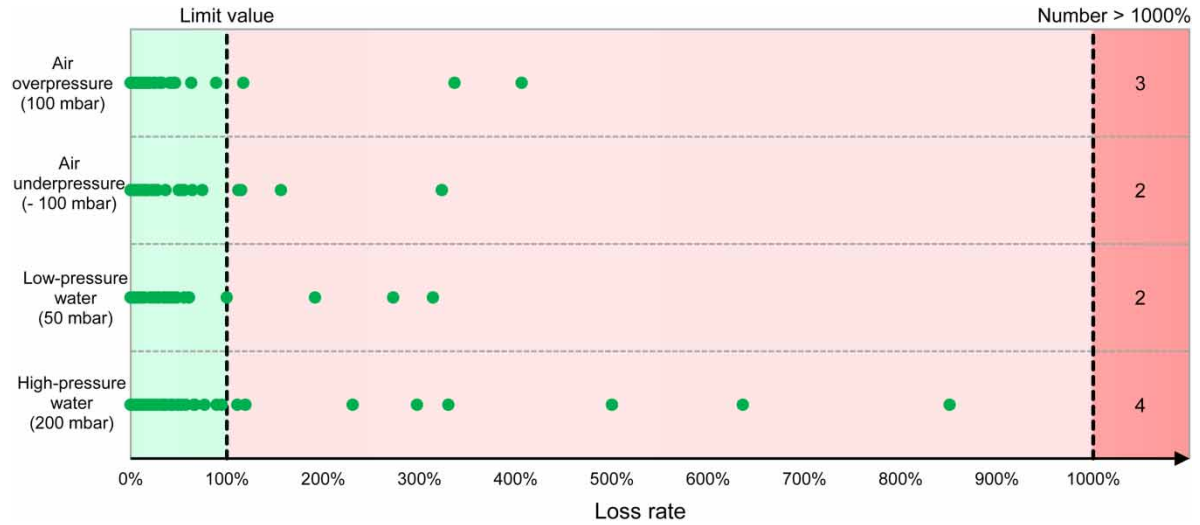




**Figure 3** | Overview of pipe states, examples: water surge (top left), flow (top right), drips (bottom left) and tight (bottom right).



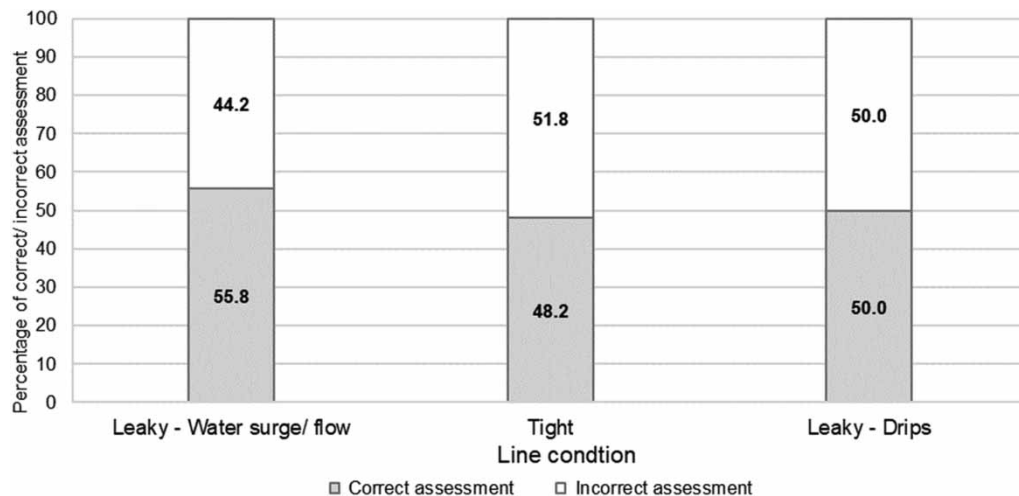
**Figure 4** | Comparative representation (normalised) of the four test methods with regard to the loss rates achieved and the resulting number of test failures for the pipe condition 'Leaky - Water Surge/Flow'.



**Figure 5** | Comparative representation (normalised) of the four test methods with regard to the loss rates achieved and the resulting number of test failures for the ‘tight’ line condition.

In the case of the ‘Leaky – drips’ pipe condition, small amounts of exfiltration and/or infiltration water were detected in six pipelines during the control measurements for determining the actual pipeline conditions, so that these pipelines were assessed as leaky (‘dripping’). However, due to the small amount of water, it could not be clearly determined whether these existing leaks would lead to a ‘pass’ or ‘fail’ test result when the leak test was carried out. Accordingly, the actual pipeline condition could not be determined with regard to the limit value specified in the test specifications. Therefore, the comparison of the actual pipe condition with the results of the expert testers was not possible to determine the reliability of the test procedures for the pipe condition ‘leaky – drips’.

During the visual inspection under practical conditions, it was examined whether infiltration-relevant abnormalities could be detected even without external water pressure. Therefore, the seven expert testers were asked after completion of the respective visual inspection whether they assessed the pipeline condition as ‘tight’ or ‘leaky’. The inspectors’ assessments were then compared with the actual conditions (control measurement). The results show that for different pipeline conditions the rate for the correct assessment is approximately 48% for the case ‘tight’ and 50% for the case ‘leaky – drips’ and approximately 56% for the case ‘leaky – water surge/flow’ (Figure 6). In Dirksen *et al.* (2011), the accuracy and reliability of condition detection (damage detection and classification) on sewers by means of visual inspections was analysed. As a result, it was



**Figure 6** | Assessment of the pipeline condition by experts after carrying out the visual inspection without external water pressure.

found that the probability of a false-positive result (damage falsely detected although none was present) was in the order of a few percent for the detection of damage patterns in main sewers. In contrast, the probability of falsely failing to detect an existing damage was about 25% (false-negative result). In the present study, in comparison, the false-negative rate of 44% and the false-positive rate of 52% are higher than the rates for main sewers in *Dirksen et al. (2011)*. However, the two studies have different objectives. In the present study, the tightness of house connection pipes was considered and in *Dirksen et al. (2011)* the condition detection (damage detection and classification) in main sewers.

Finally, the sensitivity and specificity and correct classification rate were calculated to determine the quality of the investigated test methods under practical conditions (*Table 1*). For the positive air pressure tests and the water pressure tests with low and high pressure, a sensitivity (leak confirmed) of 100%, for the negative air pressure test of approximately 99% and for the visual inspection of 56% without external water pressure was determined. The results of the specificity (leak confirmed) show that the true-negative rate for the positive air pressure, negative air pressure and water pressure test with lower test pressure according to DIN 1986-30 is approximately 90%. For the water pressure test with higher test pressure according to DIN EN 1610, a specificity of approximately 80% was calculated. In contrast, the rate for the visual inspection without external water pressure was only approximately 48%. In the overall view, correct classification rates of approximately 95% were calculated for the positive air pressure, negative air pressure and water pressure test with lower test pressure. For the water pressure test with higher test pressure according to DIN EN 1610 and the visual inspection without external water pressure, these were determined at approximately 91 and 53% respectively. This means that all test methods except for the visual inspection are assessed as reliable, since the correct classification rate for the leak test methods is, in each case, significantly above the suggested minimum value of 75% (*Schenker-Wicki 1999*).

The following recommendations are given on the **areas of application of the test methods** for carrying out tests on connection pipelines that lie above groundwater level.

Leaky pipes (pipe condition 'leaky – water surge/flow') are detected with a very high degree of reliability by all leak test methods and the test methods for this case are also robust against test errors by experts and deviations from the implementation regulations of the test standards. Even if the test is repeated as often as desired on the same test object, the test result remains stable, i.e. leaking pipes are regularly detected with all the test methods used, so that there is only a low risk of

**Table 1** | Presentation of sensitivity, specificity and correct classification rate for the individual test methods under practical conditions

Air overpressure, 100 mbar, 3 min	
Leak confirmed (sensitivity)	100.00%
Tight confirmed (specificity)	89.29%
Correct classification rate	95.49%
Negative air pressure, –100 mbar, 2.5 min	
Leak confirmed (sensitivity)	98.70%
Tight confirmed (specificity)	89.29%
Correct classification rate	94.73%
Water DIN 1986-30, 50 mbar, 15 min	
Leak confirmed (sensitivity)	100.00%
Tight confirmed (specificity)	91.07%
Correct classification rate	96.24%
Water DIN EN 1610, ground level, 30 min	
Leak confirmed (sensitivity)	100.00%
Tight confirmed (specificity)	78.57%
Correct classification rate	90.98%
Visual inspection, without external water pressure	
Leak confirmed (sensitivity)	55.84%
Tight confirmed (specificity)	48.21%
Correct classification rate	52.63%

false-negative test results. The prerequisite, however, is sufficient qualification of the experts and high reliability of the equipment technology used.

Tight pipes, on the other hand, can also be falsely classified as 'leaking' to a significant degree during leak tests. Even for the more reliable test methods, i.e. air overpressure, air underpressure and water with low test pressure, a tight pipe is falsely classified as leaking (false positive) in one out of 10 cases. The highest false-positive rate was encountered with water with high test pressure, in the order of about 20%.

All of the leak test methods used showed this lack of reliability in the correct detection of tight pipelines. Uncertainty due to 'false-positive results' is a fundamental problem, since complex tests often lack control options or are extremely complex in order to definitively exclude errors or unsuccessful test procedures. However, the test results suggest that confidence in the reliability of the test statements can be ensured by carrying out an independent repeat test; this applies to pipelines evaluated as leaking with a maximum acceptable error rate of e.g. 1%.

When comparing the leak test methods with each other, it was found that the results of the air pressure tests tend to be more precise than those of the water pressure tests.

The use of visual inspection is generally recommended for the rehabilitation acceptance with regard to the goals of 'operational safety' and 'stability'. With regard to the proof of exfiltration tightness, however, the results of the visual inspection in the tests carried out show clear weaknesses and only in exceptional cases lead to meaningful results at all (correct classification rate of approximately 53%), e.g. in the case of severe leakage in the pipe shaft area (broken pieces, missing pipe wall, etc.). In contrast, in a comparison of the test methods considered (air, water, visual inspection), the detection of infiltration tightness of connection pipes under external water pressure is most likely to succeed on the basis of visual inspection.

In order to increase the reliability of the leak tests, errors in the execution of leak tests in particular must be avoided. For this purpose, the correct pipeline data must be recorded and correctly entered into the testing software by the expert tester. In addition, a suitable test sensor should be selected for the test pressure range and the measuring accuracy of the measuring technology used should be checked at one-year intervals. Before the test is carried out, a reference measurement should be made with the test equipment to check the performance. In order to prevent water creep, suitable shut-off elements should be selected and the inner pipe surfaces in the area of the shut-off elements should be cleaned. In addition, the correct placement of shut-off elements can be observed by means of an inspection camera. In principle, an annual functional check of the shut-off elements should be carried out. The [DWA-A 139 \(2019\)](#) and [DWA-M 149-6 \(2016\)](#) standards provide information on the requirements, inspection and use of shut-off elements. During a water pressure test, a shut-off element with float should be used to vent the pipe. The float must be freely movable in the wastewater pipe to be tested, be very flexibly connected to the shut-off element and be able to float up to the apex. In order to achieve meaningful test results, the test requirements set out in the respective standards and regulations must be complied with by the expert tester. These include, among others, settling or preparation time, test time and test pressure for the air or water tests. For the test start pressure, [DIN EN 1610 \(2015\)](#) requires that the required start test pressure is exceeded by about 10%. Subsequently, the test pressure must be set according to the stated test requirements. However, our own and observed test procedures show that the test pressure cannot be set exactly to the test start pressure as required. Due to the impracticability of these requirements, a tolerance limit of  $\pm 10\%$  should be specified and taken into account in the test specifications. In addition, a correct placement of the measuring sensor during the water pressure test (ideally at the apex of the pipe) must be carried out so that a correct measurement is made. If this is not possible, height differences must be taken into account. Finally, it should be noted that there are many standards and regulations in the field of leak testing from different associations and institutions, which sometimes create a confusing overall picture when viewed together. Against this background, a comprehensive standard for leak tests should be drawn up so that all essential test requirements are listed in a standardised way in one document.

## CONCLUSIONS

Within the scope of the present study, the quality of various test methods for leak testing and visual inspection of wastewater connection pipelines was determined for the first time on the basis of empirical investigations. The leak tests and visual inspections were carried out on a 1:1 scale test facility under practical conditions. The results of approximately 1,000 individual tests were descriptively evaluated, analysed and evaluated using statistical methods. On this basis, specific recommendations for action could be given, which make the testing of connection pipelines more reliable during rehabilitation acceptance, especially with regard to achieving the technical service life of wastewater pipes.



The test results according to DIN EN 1610, DIN 1986-30 and DWA-A 139 showed that leaking pipes are detected with a very high degree of reliability by all leak test methods. These test methods are also robust against test errors by expert testers and deviations from the test specifications. There is only a low risk of false-negative test results. The prerequisite, however, is sufficient qualification of the expert testers and high reliability of the equipment technology used.

In contrast, tight pipes can also be falsely classified as 'leaking' (test failed) to a significant extent. Even for the more reliable test methods, i.e. air overpressure, air underpressure and water with low test pressure, a tight pipe is falsely classified as leaking (false positive) in one out of ten cases. The highest false-positive rate was encountered with water at high test pressure in the order of about 20%. All of the leak test methods used showed this lack of reliability to correctly detect leaking pipes. In this case, an independent retest could improve the reliability from about 90% to 99%.

In addition to the leak test methods, the quality of the visual inspection was also analysed. It was found that visual inspection is not sufficiently reliable for determining the tightness of pipes above the groundwater level to reliably fulfil all normative requirements. However, if in contrast the pipe is located in groundwater, visual inspection provides extremely reliable information on the tightness of connection pipelines. In addition, the visual inspection also provides information on the stability and operational safety of the pipes.

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## DATA AVAILABILITY STATEMENT

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

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