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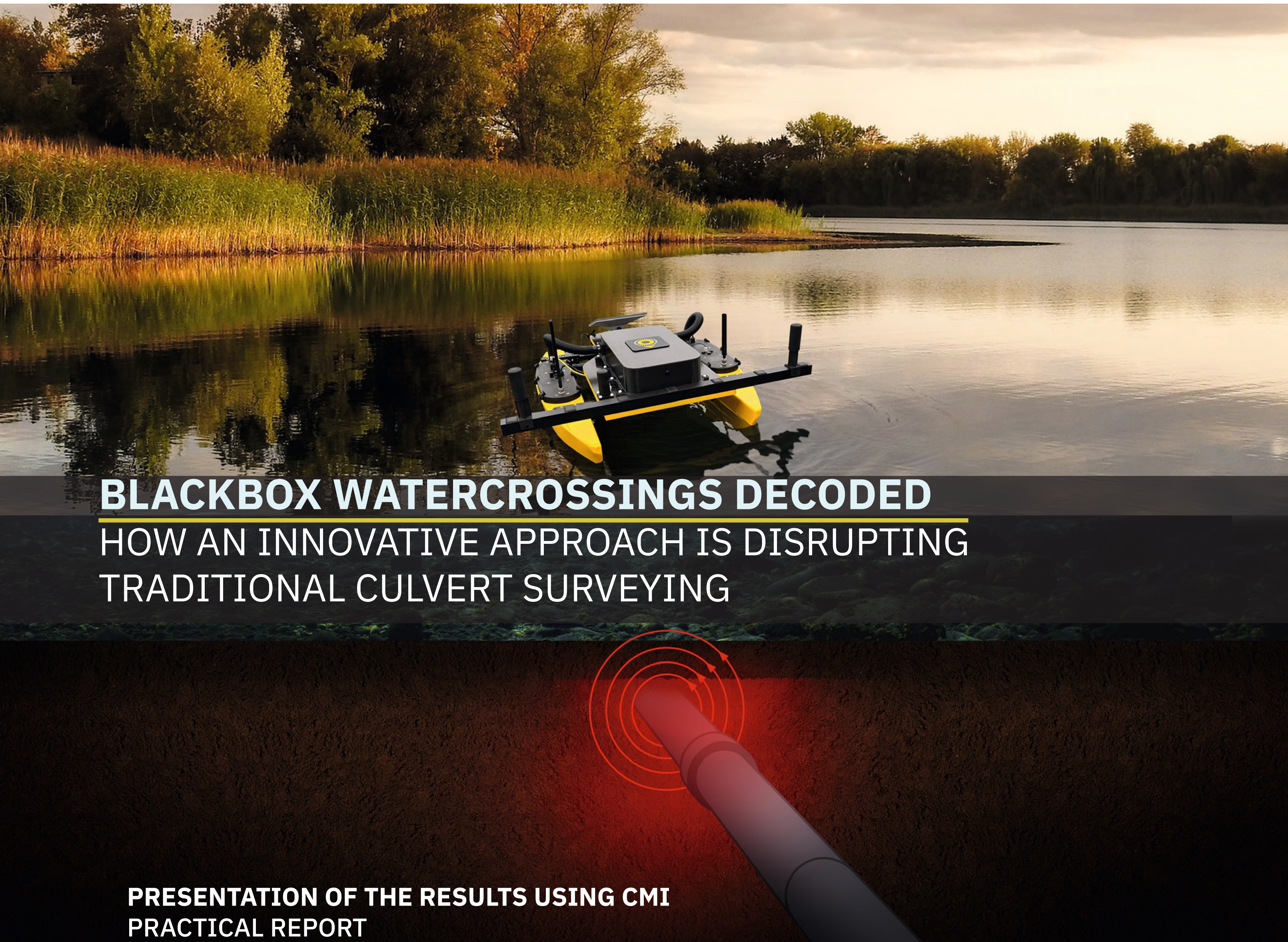

BLACKBOX WATERCROSSINGS DECODED

HOW AN INNOVATIVE APPROACH IS DISRUPTING TRADITIONAL CULVERT SURVEYING

PRESENTATION OF THE RESULTS USING CMI

PRACTICAL REPORT

EMPIT

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Effective Risk Management through Precise Culvert Surveying using CMI

By Jakob Stumme, Mark Glinka and Kay Peschke

Pipelines known as culverts cross water bodies and other infrastructures such as roads. They pose a particular challenge for risk management. Especially when verifying the position and depth of cover (DoC) of pipelines crossing water bodies, conventional inspection methods reach their limits. The innovative inspection technology developed by EMPIT GmbH – Current Magnetometry Inspection (CMI) – now offers an alternative. The AI-supported process enables precise determination of pipeline position and it's DoC. Practical examples from German network operators demonstrate the performance of the process.

Background

In the past century, thousands of kilometers of pipeline networks for transporting gases and liquids have been laid worldwide. Culverts, which enable crossings of roads, railways, cables, or other pipeline routes, as well as water bodies, are an essential component of these pipeline networks. The special location of culverts often leads to enormous effort and costs in the event of pipeline failure, for example, at busy roads or to increased environmental risks near bodies of water.

In flowing water bodies, scouring of the riverbed and banks can occur over time.

Table 1: Technical specifications of the CMI system for culvert surveying

Max. error during position determination (RTK FIX GNSS)	4 cm
Resolution radar / lidar / sonar (rad/lid/son)	1 cm
Max. water depth	50 m
Max. error in depth determination	
Depth: <1,5 m	1 %
Depth: 1,5 – 4 m	2 %
Depth: >4 m	3 %
Max. error during DoC determination	$\sigma_{rad/lid/son} + \sigma_{depth}$

If the pipeline is displaced, e.g., due to uplift, there is also a risk that the overlying material will be washed away. Both effects lead to a reduction in the DoC, even potentially exposing the pipeline. Water bodies with active shipping represent a particular risk. Here, external factors such as protection against anchors or chains must be accounted for with sufficient coverage. When it comes to pipeline exposure, the risk for unstable positioning increases, alongside with the risk of sediment collisions. Furthermore, local dynamic stresses caused by currents or shipping traffic increase the risk of deformation. This can lead to changes in the fracture mechanics of pipelines, increasing the risk of pipeline failure.

Restoring the necessary minimum DoC varies depending on the required measures. Simple backfilling with suitable material can provide short-term remedy but is often not permanently effective due to erosion and currents. Further erosion protection measures, such as stone or concrete mats, or reinforcement of pipelines, require construction below the water surface and involve high costs and planning effort. If these measures are insufficient, relocating the pipeline may be necessary, which is the most expensive and labor-intensive solution.

Especially for pipelines under water bodies, failure can have severe ecological consequences depending on the transported medium.

Therefore, the technical regulations of the DVGW (German Technical and Scientific Association for Gas and Water) (GW 304 and GW 315 [1,2]) recommend.

Current status to determine the DoC of pipelines crossing water bodies

Common methods for locating buried pipelines include ground-penetrating radar (GPR), acoustic, or seismic methods. These methods are based on a similar principle: a signal (acoustic or electromagnetic waves) is emitted into the ground and reflected by geological layers and objects. The reflected signals are then used to determine the position and coverage of pipelines. However, the effectiveness of these inspection methods and the penetration depth of the signals are highly dependent on the nature of the subsurface. For example, with GPR, penetration depths of only up to 1 m can be expected in wet clay, which is often found at the bottoms of water bodies [3,4]. The interaction of different soil layers, such as at riverbanks, can also lead to significant uncertainties in determining the correct location and DoC [3,5]. As a result, making reliable statements about the precise location of buried pipelines and their DoC are often not possible.

Another method involves detecting ferromagnetic pipelines through magnetometry in the Earth's magnetic field. Under favorable conditions, it is possible to locate pipelines buried several meters deep and determine their coverage.

However, the magnetic fields are not applied under controlled conditions during the inspection, which makes the measurement dependent on external factors such as the global orientation of the pipeline and the associated pre-magnetization or interference from external influences from the environment. Additionally, for pipelines at greater depths, the resulting measurable magnetic field is correspondingly small (Figure 1), requiring measurements in grid fields. The influence of external factors and the challenging handling of the large datasets produced make the evaluation of these measurements demanding. This contributes to the fact that classic magnetometry has not yet been used as a common method for locating pipelines.

Furthermore, bathymetry can be used to monitor ground level changes or to be cross-referenced with results from inline technology inspection (ILI) methods. However, monitoring ground level changes can only give an indication of DoC changes but for example does not take pipeline movement into account. As ILI focuses on different aspects during inspection, the determined absolute position often has a high uncertainty. Overall, there are several factors compromising the reliability of obtained results.

To balance the risk posed by insufficient cover against the massive expense of a remedial measure, accurate and reliable inspection data is essential. However, the methods described above often fail to provide such reliable information for water crossings or are burdened with significant uncertainties.

The Current Magnetometry Inspection (CMI) method, developed by EMPIT GmbH, enables precise pipeline location using magnetic field measurements generated by a self-applied alternating current.

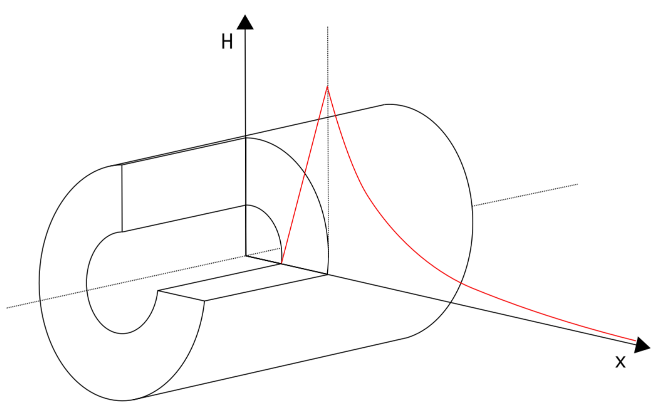

Figure 1: Schematic representation of the measurable magnetic field (H) as a function of the distance of the pipe axis (x)

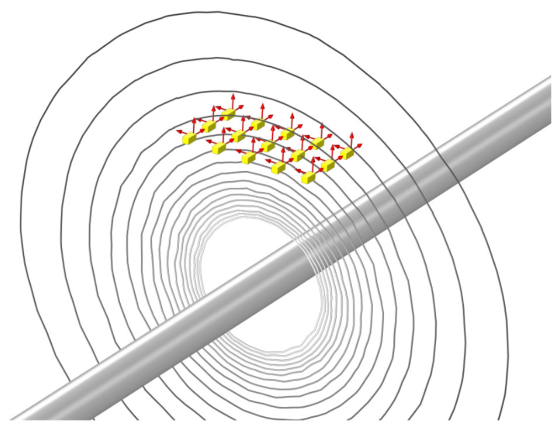

Figure 2: Schematic representation of the eddy magnetic field around the pipeline and the arrangement of the sensors for

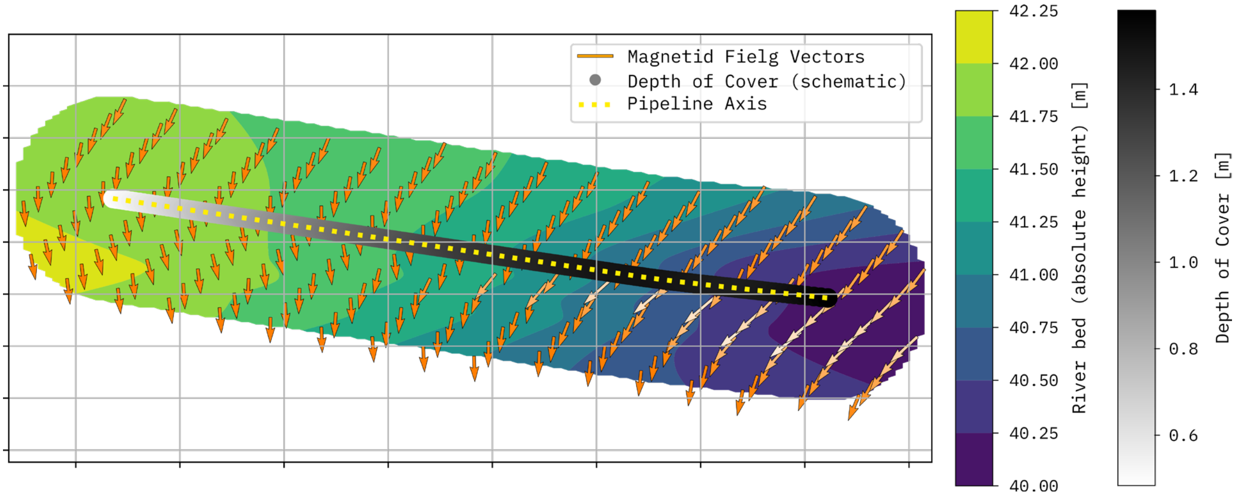

Figure 3: Exemplary representation of a pipeline in XY view with the magnetic field vectors; in addition, the depth of cover of the pipeline and the absolute height profile of the waterbed are indicated by the color scaling

A multisensor system was developed for this purpose, which, through the use of Deep-Fusion AI, allows for a novel inspection approach that delivers reliable measurement results. Various land-, air-, and water-based systems enable inspections regardless of the terrain.

By integrating lidar, radar, or sonar systems, the terrain surface and, consequently, the precise DoC can be determined in a single inspection run. To date, more than 10,000 km of pipelines have been inspected using this method. The CMI system is certified as a location method and is now used by most German long-distance pipeline operators, increasingly also for the inspection of culverts crossing water bodies. The CMI method is described in more detail below.

The CMI (Current Magnetometry Inspection) method

During CMI, an alternating current with a multi-frequency signal is applied to longitudinally conductive pipelines.

The inspection current generates a magnetic eddy field around the pipeline. By using a self-applied inspection current, the resulting magnetic eddy field is known and controllable during inspection. This makes the location of the pipeline independent of external factors or geographical conditions, which is the biggest difference to the magnetometry described above.

The magnetic eddy field is detected and evaluated from the ground or water surface using up to 20,000 measurement points per second with up to 70 sensors.

The spatially distributed arrangement of the sensors (Figure 2) enables the magnetic field to be vectorially captured in all three spatial directions, as exemplary shwon in Figure 3. Using this measurement data, it is possible to determine the current in the pipeline and the distance of the pipeline from the inspection system at any given moment.

Additionally, during the inspection, the distance of the measuring systems to the terrain surface is recorded using lidar, sonar, or radar systems, as well as the system‘s orientation (e.g., inclination).

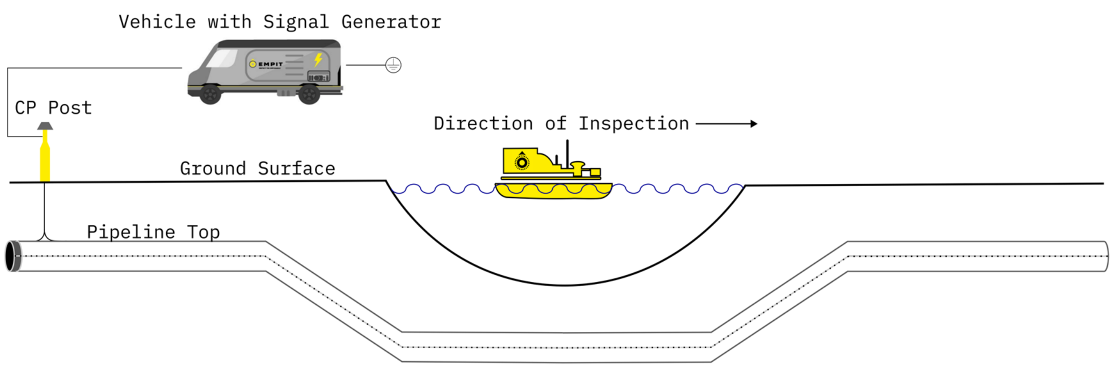

Figure 4: Schematic diagram of the inspection setup with the CMI boat as the inspection unit

Figure 5: Overview of CMI inspection systems with examples of individual versions

This makes CMI the most precise inspection system globally for 3-dimensional position determination, even for complex geometries. This level of precision also allows for seamless and reliable DoC assessments of buried pipelines, regardless of the terrain.
For the inspection, a combination of at least four frequencies in the range of 2 to 2,000 Hz is applied to the pipeline. These frequency ranges are virtually unaffected by soil layers, unlike the frequencies used in GPR, for example.

Moreover, using multiple frequencies allows to distinguish the pipeline from external structures, which is a major advantage over magnetic field measurements in the DC field. Furthermore, the use of alternating current enables inspections to be conducted without interrupting the pipeline operation. Cathodic protection (CP) systems can also continue to operate normally during the measurements.
In general, the CMI measurement equipment consists of three components: the signal generator (SG), the inspection system, and an intelligently connected data system. The setup during the inspection is schematically illustrated in Figure 4.

The signal generator (SG) is connected to the pipeline via galvanically connected elements (e.g., CP measurement posts, valves, or rectifier systems) and is responsible for the safe and reliable provision of the inspection current. Intelligent optimization processes are used to match the inspection current to the local electromagnetic and geometric conditions. This makes the inspection independent of external AC and DC influences, enabling the inspection of pipelines heavily influenced by external currents.

The inspection systems (Figure 5) are digitally connected directly to the SG via the data system. During the inspection, the current values calculated from the magnetic field are transmitted to the SG in the millisecond range. The SG continuously adjusts the optimal signal-to-noise ratio based on the transmitted data. This temporal correlation between the SG and the recorded measurement data enables signal normalization at any point during the measurement. This provides additional information, from which further data can be determined, for example, information on the condition of the pipeline at coating defects.
Over the years, inspection systems have been continuously developed and refined.

In addition to land-based systems, airborne systems, with the use of drones, and water-based systems, such as inspections with boats or submersibles, are now also used. The evaluation is based on advanced and ever more sophisticated algorithms that make it possible to process large volumes of data. For pipelines at depths of up to 7 m, a single inspection run is usually sufficient. For pipelines at greater depths, the accuracy of the calculations can be significantly improved by grid measurements.

The inspection of offshore pipelines in water depths of up to 3000 m will be possible in future using intelligent water vehicles (ROVs, Remotely Operated Vehicles). EMPIT GmbH is currently being supported by the German Federal Ministry for Economic Affairs and Climate Action in order to drive development forward efficiently.

Accordingly, CMI is independent of the surface conditions above the pipelines and offers an excellent solution for culvert sounding in any terrain.

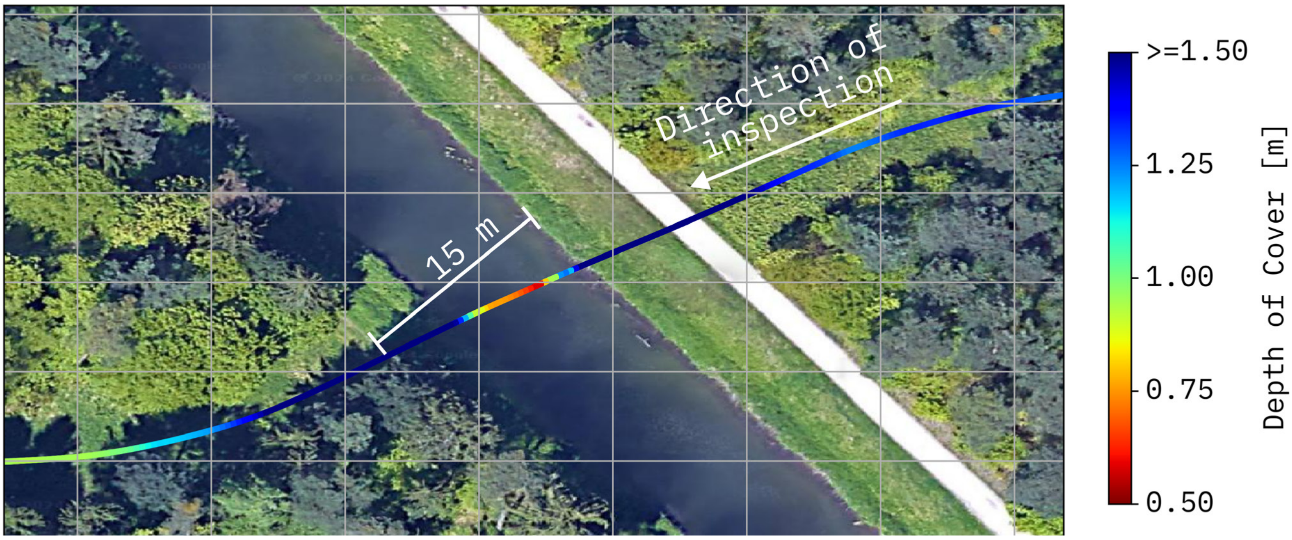

Figure 6: Crossing of the pipeline route with the canal; the coloring of the pipeline correlates to the indicated DoC at the respective position

Inspection Results

EMPIT GmbH, in collaboration with Avacon Netz GmbH, has successfully inspected culverts of varying complexity. The three case studies presented here involve culvert surveys below flowing surface water bodies, differing in the size of the respective water body.

Case 1: Correction of GPR inspection results using CMI

The first inspection involves a steel transport pipeline (DN 660) crossing a canal approximately 15 m wide and 2.5 m deep in a forested area. Initially, the pipeline was located using the aforementioned GPR method, also determining DoC. GPR consistently reported a sufficient DoC exceeding 2 m.
However, manual controls by the pipeline operator revealed discrepancies, which called into question the reliability of the results. Consequently, the crossing was reinspected using the CMI method.

Figure 6 shows the top view of the absolute position of the pipeline. The color scale of the route indicates the DoC at the respective position. Figure 7 (top) displays the cross-section of the terrain along the pipeline, including the ground surface, water surface, canalbed, and the position of the pipeline. Additionally, a dashed line represents a theoretical DoC of 2 m. Figure 7 (bottom) provides the DoC profile along the pipeline route.

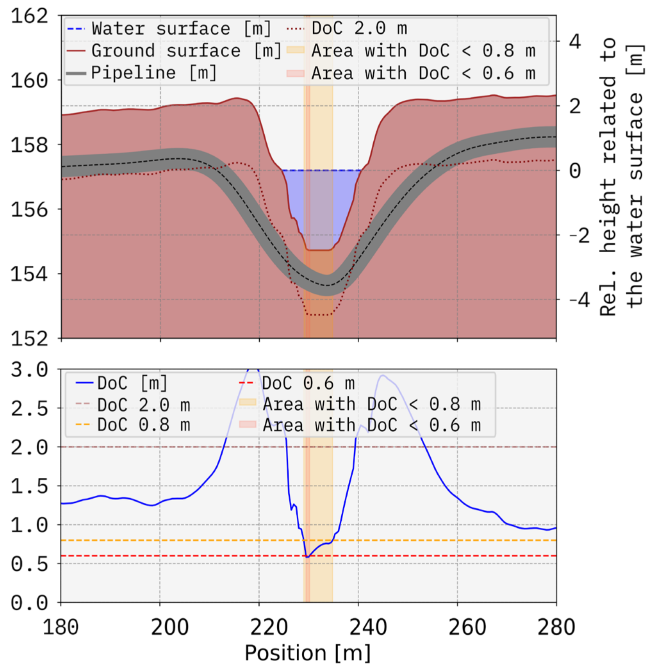

Figure 7: Top: Terrain, water surface and pipeline profile over the length; the dashed line indicates a theoretical DoC of 2 m, which was specified as the minimum cover for a GPR inspection. Below: Course of the DoC over the length of the pipeline; colored are areas with inadequate DoC (<0.8 m or <0.6 m)

It is immediately noticeable that in large areas, the DoC does not exceed 2 m. The pipeline's depth in the forested sections before and after the water body ranges from 1 to 1.5 m. Only in the area of the outer culvert, where the pipeline descends while the terrain remains relatively flat, does the DoC increase to more than 2 m, even reaching up to approximately 3 m. The situation is different in the section where the pipeline crosses the canal.

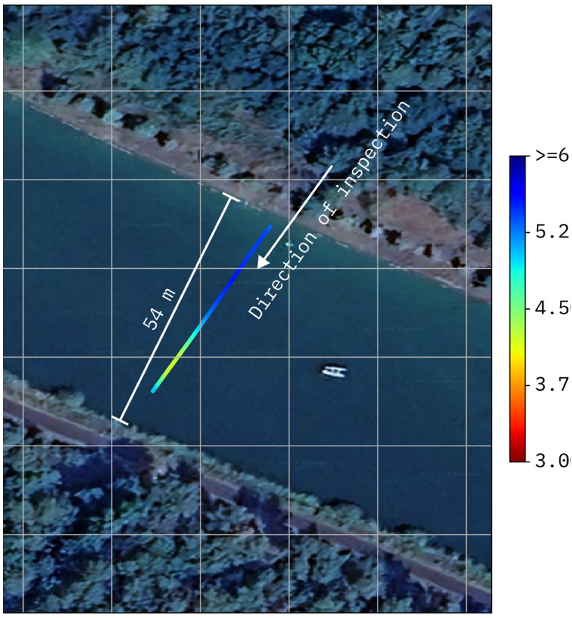

Figure 8: Pipeline route under the canal; the coloring of the pipeline correlates to the DoC at the respective position

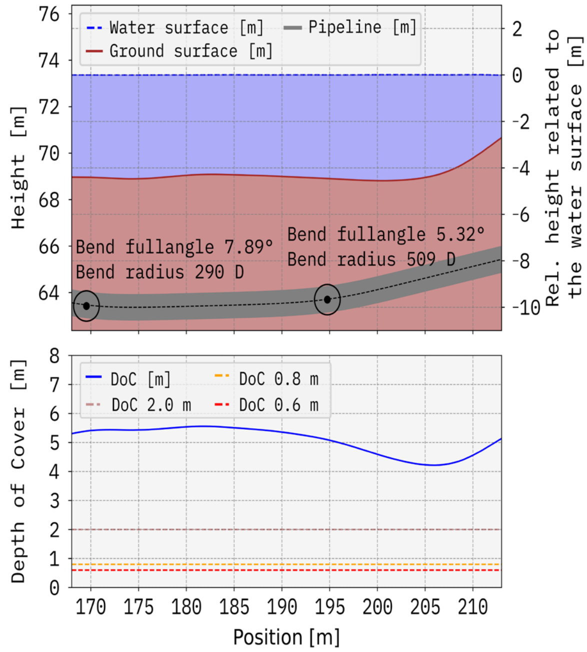

Figure 9: Top: Terrain cross-section over the length of the pipeline with top edge of the canal, canal ground and pipeline; additionally, the identified bends >2° in the inspected area are indicated with full angle and bend radii. Below: DoC over the pipeline length of the selected inspection section

Here, the DoC falls well below 2 m. In the yellow-colored area (approximately 5 m wide), the DoC is less than 80 cm, while in the red-colored area (approximately 1 m wide), it is less than 60 cm. These results of insufficient coverage align with the controls performed by the operator. Accordingly, the CMI enabled a precise culvert survey, met expectations, and provided essential information for the operator's risk management.

Case 2: Verification of DoC in an actively navigated canal

In the second case, the pipeline crosses a canal actively used for shipping. The canal is approximately 55 m wide, with a water depth exceeding 4 m at the time of inspection. The waterway accommodates large motor cargo vessels of up to 2,000 t and push convoys with lengths of 185 m, weights of 3,500 t, and drafts of 2.8 m.

This poses an increased risk of damage to the pipeline from external factors such as anchors or chains. Additionally, dynamic mechanical stresses caused by shipping, changes in water levels, currents, and associated sediment displacement can burden pipelines that are inadequately protected or have insufficient DoC. These risks necessitate precise location methods and regular monitoring to ensure the long-term safety and integrity of pipelines under water. Accordingly, the inspection focused on the middle of the waterway with shipping traffic.

Figure 10: The CMI boat „Yellow-Fin" on the shore shortly before inspection

Figure 11: Crossing of the pipeline route below the river; the coloring of the pipeline correlates with the determined DoC at each respective position

Despite a distance of up to 10 m between the pipeline and the inspection system, the pipeline was successfully located, and the DoC was reliably determined. The pipeline route in the inspected area, along with the terrain cross-section over the pipeline length showing the ground surface, water surface, and riverbed, is illustrated in Figure 8 and Figure 9 (top), respctively. The DoC profile is represented by the color scale in Figure 8 and as a plotted profile in Figure 9 (bottom).

Inspection results show that, in the central part of the canal the pipeline had sufficient coverage exceeding 5 m in large areas. The pipeline rises towards the edges of the canal, but was also adequately protected by the soil here with a cover of >4 m. Additionally, Figure 9 shows pipeline bends greater than 2° as combined bends (combined vertical and horizontal components) and corresponding bend radii. In the inspected section, no major bends exceeding 10° were detected.
The bend radii, all greater than 200 D, pose no restrictions for further condition assessments, such as those using inline inspection technology.

Overall, at the time of inspection, due to sufficient DoC, the risk of damage to the pipeline from external factors was deemed low, ensuring safe operation alongside active shipping.

Case 3: Culvert survey below a 215-meter-wide river

In the third case, the inspection involved a transport pipeline (DN 600) crossing a river approximately 215 m wide and up to 2.5 m deep at the time of inspection.

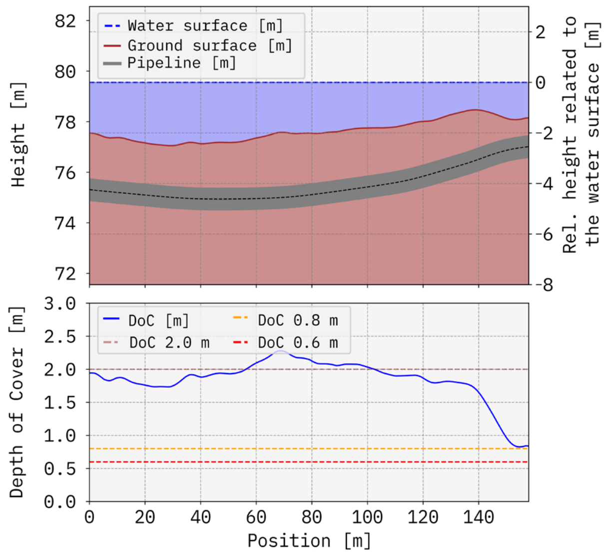

Figure 12: Top: Cross-section of the terrain along the pipeline length, showing the water surface, riverbed, and the position of the pipeline. Bottom: DoC along the pipeline length for the selected inspection section

This section of the river is only partially used for navigation.
The pipeline's route and profile are presented in Figures 11 and 12, along with the DoC.
The pipeline's route in the top XY-view is unremarkable, as it runs predominantly straight, which aligns with expectations. In the cross-section, the pipeline maintains a depth of cover between 1.7 and 2.2 m across a wide area of the river. Towards the eastern edge of the water body, the pipeline rises more steeply than the riverbed, resulting in a reduced DoC.

However, as the pipeline approaches the riverbank, it levels out, ensuring a minimum DoC of 83 cm, with no sections falling below the critical threshold of 80 cm (German regulations).

Given the shallow water depth and limited shipping activity in this section of the river, no special regulations regarding DoC apply. Therefore, sufficient coverage was ensured throughout the inspected area at the time of inspection.

Overall, EMPIT GmbH was able to provide comprehensive information about the pipelines in the relevant areas for all inspections conducted. Both the absolute position and the DoC, on land and under water, were determined in a single inspection run. The results were digitized and partially validated through exposure and manual probing. The measurement specifications outlined above were fully complied with. As a result, introducing the the CMI technology has made it possible, for the first time, to obtain precise and reliable results for culvert surveys. These results are independent of external factors or soil conditions. The information obtained through CMI thus makes an essential contribution to effective risk management for pipeline operators.

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