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# Investigation of Disc Cutter Wear in Tunnel-Boring Machines (TBMs): Integration of Photogrammetry, Measurement with a Caliper, Weighing, and Macroscopic Visual Inspection

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**Abstract:** During the construction of tunnels using tunnel-boring machines (TBMs), the wear of disc cutters is an unavoidable process. The timely replacement of worn disc cutters can have a positive effect on construction time and therefore on costs. The wear of disc cutters can be assessed using various measurement methods. The aim of this article is to show different methods of measuring and evaluating the wear of disc cutters and to present their main advantages and disadvantages. In this study, four different wear-measuring methods were used and applied to a worn double disc cutter: a macroscopic visual inspection, profile measurement with a caliper, weighing, and close-range photogrammetry. The results of the measurements showed that the worn disc cutter was subject to normal abrasive wear, with local steel chipping occurring. Based on the close-range photogrammetry measurements, a profile of the worn disc cutter was also created and compared with the original profile. It was found that the best results for the wear assessment of a disc cutter can be achieved by using several measurement methods simultaneously. The integration of different measurement and evaluation methods is therefore recommended for a comprehensive understanding of disc cutter wear.

**Keywords:** TBM; tunneling; disc cutter; wear



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## 1. Introduction

In the construction and mining industry, tunnel-boring machines (TBMs) play a crucial role in excavating tunnels for various infrastructure projects. These machines use disc cutters as important tools to break rock during tunnel construction. The disc cutters are installed in the front part of the TBM's cutter head at a specific radial distance. The rotation of the TBM's cutter head causes the disc cutters to roll, whereby their rolling speed depends on the rotational speed (RPM) of the cutter head and the radial installation position. The position of the disc cutter in the cutter head affects the amount of physical work it performs within a certain period of time, which is related to the wear of the disc cutter. In addition, the disc cutter is subjected to very high stresses due to the considerable load force acting on a relatively small contact area between the rock and the tip of the disc cutter. During TBM tunneling, especially in hard and discontinuous rock masses, stresses can sometimes reach extremely high values.

The wear resistance of disc cutters in tunnel construction using TBMs is a decisive aspect of their performance and durability. Studies by Cardu and Giraudi [1] and Lin et al. [2] have shown a correlation between the wear of disc cutters and material factors such as hardness and toughness. Cardu and Giraudi [1] emphasized the influence of hardness on wear resistance and pointed out the importance of matching the microhardness of the cutter to the hardness of the rock. Similarly, Lin et al. [2] showed that the wear properties of disc cutter rings are determined by their hardness and toughness and discussed the significance of material properties in wear resistance.

As stated by Zahiri Galeshi et al. [3], the accurate prediction of the wear of disc cutters is important for optimizing the performance of TBMs and minimizing costs. This study explores the detrimental effects of exceeding the critical wear values of disc cutters, which not only reduces the efficiency of disc cutters but also increases stresses and potentially leads to bearing damage or sealing issues. In addition, the causes of disc cutter replacement vary depending on their position. Problems such as gripping or jamming often occur to disc cutters installed in the center of the TBM's cutter head, while fractures and cracks can be observed in disc cutters on the periphery of the cutter head. Normal wear, crushing, and mushrooming have been identified as the main causes of damage to all discs and are responsible for a significant proportion of replacements. Improving resistance to these factors could therefore significantly extend the service life of disc cutters.

In recent studies in the literature, various strategies have been investigated to improve the performance and durability of disc cutters under different material and manufacturing conditions. Studies by Zhang et al. [4] and Hu et al. [5] focus on the design of disc cutters, their material composition, and processing techniques to improve wear resistance. These studies underline the influence of factors such as the diameter, shape, and material composition of disc cutters on wear resistance and provide valuable insights to optimize their performance in difficult operating environments. Zhang et al. [4] also investigated the remanufacturing of H13 steel disc cutters and presented advances in repair techniques. They point out the advantages of remanufacturing technology in improving energy and material utilization, which ultimately increases cutting efficiency and reduces production costs. Hu et al. [5] proposed the optimization of processing technology by analyzing factors such as blank size, heating temperature, preheating temperature, and the friction coefficient to determine optimal forming parameters. Their research discusses the importance of suitable heat treatment processes, such as high-temperature quenching and tempering, to improve the material properties and performance of disc cutters. By using ring-shaped blanks and conducting compression and hardness tests, the study shows the significance of maintaining material hardness and compressive strength, especially at high temperatures.

Some studies also demonstrate the importance of optimizing operating parameters to reduce wear on cutter discs. Hassanpour et al. [6] and Cho et al. [7] investigated the relationship between the rotational speed of a TBM's cutter head and the position of its disc cutters and their wear. As discussed by these authors [6,7], it is crucial to control factors such as torque, thrust force, advance rate, and rotation speed to extend the service life of a disc cutter and reduce maintenance.

In addition, advances in models for estimating the wear of disc cutters, as discussed by Hassanpour et al. [6], provide crucial insights for accurately assessing the operational behavior of disc cutters under different geological conditions. Understanding the forces acting on rock during cutting, as studied by Rostami [8], also contributes to improving the design of disc cutters. Predictive models also include various computer simulations and machine learning methods to estimate the wear of disc cutters. Finite element analyses (FEAs) and the discrete element method (DEM) are commonly used to predict the wear of disc cutters under different operating and geological conditions. Moon and Oh [9] and Choi and Lee [10] used the DEM and particle flow code (PFC3D) to analyze the behavior of disc cutters and demonstrate their effectiveness in predicting wear patterns and failure aspects. They showed that a DEM-based simulation can better represent microcracks in rock material. Agrawal et al. [11] used the DEM to analyze the effects of disc cutter features, including tip angles and tip widths, on wear. Their results indicated that the tip angle and penetration depth have a direct effect on cutter wear. Xue et al. [12] used the PFC3D to simulate the evolution of cutter chipping. They found that the cutting speed and an increase in penetration depth increased the probability and intensity of cutter chipping. The presence of initial defects also had a negative effect on the service life of the disc cutter.

It should be noted that numerical modeling is a complex process that requires experience in computational methods, material characterization, and wear physics. Validating numerical models with experimental data is crucial to ensuring the accuracy and reliability of predictions. Obtaining the data required for numerical modeling can also be time-consuming and costly. This includes obtaining detailed material properties for the rock and disc cutter and conducting experimental laboratory tests and extensive data analysis. In addition, the exact tunneling parameters must be taken into account. All these factors should be considered when implementing numerical modeling as a tool for wear analysis as they may affect the overall feasibility and practicality of the approach.

In contrast to numerical modeling, which relies heavily on explicit equations and physical principles, machine learning (ML) methods learn from large data sets containing experimental observations and possibly simulated wear data. By recognizing complicated patterns and relationships directly from these data sets, machine learning models bypass the need for explicit model parameterization and the manual formulation of wear physics.

These methods are complex algorithms, often involving artificial neural networks (ANNs), adaptive neuro fuzzy inference systems (ANFISs), and support vector machine (SVM) analyses, as presented by Tiryaki [13], Iphar [14], Zhou et al. [15], and Kilic et al. [16], who developed data-driven models for predicting wear based on operational parameters. Tiryaki [13] used an ANN to predict the cuttability of rock with drag tools, while Iphar [14] used an ANN and ANFIS to predict the impact performance of hydraulic hammers. Zhou et al. [15] highlighted the effectiveness of SVMs along with other techniques in developing data-driven models for predicting wear based on operational parameters, particularly the TBM advance rate. Kilic et al. [16] found that their proposed one-dimensional convolutional neural network (CNN) established a strong correlation between machine parameters and the wear index of the disc cutter during tunneling in soft soils. It is important to point out that the use of machine learning models is often associated with problems such as overfitting, the need for large data sets for training, the complexity of calculations, and the interpretability of models.

Several authors [7,11,12,17–21] have noted that monitoring the wear condition of disc cutters and implementing predictive maintenance strategies are crucial to operational efficiency and cost management. Detailed discussions of wear measurement methods can be found in the following chapters, in which each method is examined in depth.

This article explains the factors that influence the wear of disc cutters during the operation of TBMs. This study discusses the relationship between various parameters of disc cutters—such as diameter, material composition, and design features—and their performance. By investigating the interplay between the parameters of disc cutters and their performance, including their wear behavior in different tunneling scenarios, important insights are gained for the optimal monitoring or selection of wear measurement methods.

The focus of this study is on methods used for measuring and evaluating the wear of disc cutters. Although general measurement techniques are discussed, the focus is on the methods used in the case study of disc cutter wear. These techniques include various approaches such as close-range photogrammetry, profile analysis, weighing, and visual macroscopic inspection. Of particular importance is the application of close-range photogrammetry, a novel method for quantifying the wear of disc cutters. This innovative approach involves photogrammetric processing to generate a dense point cloud and a three-dimensional model. The point cloud serves as a basis for comparing worn disc profiles with reference profiles derived from disc production plans. In addition, the 3D model facilitates the comparison of volume and mass losses to gain a comprehensive insight into the extent of wear of the disc cutter.

The knowledge gained about the wear characteristics of disc cutters and the methods through which wear can be best observed, combined with the innovative approach to wear measurement used in this study, will enable engineers and operators to make informed decisions about monitoring the wear of disc cutters. Ultimately, this knowledge can drive the optimization of TBM tunneling processes and lead to improved productivity and cost-efficient project execution.

### 1.1. Disc Cutter Sizes and Applications

Disc cutters are important tools for mechanized tunneling using tunnel-boring machines (TBMs). In general, the size of disc cutters increases with the diameter of the TBM's cutter head. Choosing the right disc size plays an important role in efficient rock removal and excavation. For TBMs with larger cutter head diameters of more than 5 m, disc cutters with diameters of 432 mm (17″) to 483 mm (19″) are generally used [8,22–24]. These larger disc cutters are suitable for major tunneling projects, especially in hard rock with a high compressive strength, where high cutting forces are required for efficient rock breaking.

Smaller disc cutters are used for microtunneling projects in which microtunnel-boring machines (MTBMs) are equipped with cutter head diameters of up to about 4 m. Disc cutters with diameters of 203.2 mm (8″) to 355.6 mm (14″) are usually used for such projects [25,26]. These smaller disc cutters are suitable for minor tunneling projects, such as various utility tunnels using trenchless pipe-jacking technology in rock and soil. Regardless of the size of the disc cutter, its function is the same for all tunneling projects, namely breaking the surrounding rock on the tunnel face.

The breaking of the rock is caused by a high concentration of stresses under the tip of the disc cutter. When the stress locally exceeds the strength of the rock, radial tensile cracks are formed, while rock fragments (or rock chips) are created when the cracks reach the free surface or when they interact with other cracks formed by adjacent cuts [7,27].

### 1.2. Components and Design of Disc Cutters

A disc cutter consists of a cutter shaft, bearing, cutter body, and cutter ring. The cutter ring is the component that is in direct contact with the mined rock [28]. It is primarily responsible for the cutting action and wears out during mining. The cutter ring is usually made of hot-work tool steel, which is characterized by high strength and toughness with high hardness and wear resistance [29–31]. The other components of the disc cutter already mentioned are necessary for its proper function. They ensure the support and stability of the cutter ring during the cutting process using a tunnel-boring machine.

Disc cutters are designed with one or more cutter rings, depending on the specific requirements of the tunnel project. Single-disc configurations consist of a single cutter ring, while double-disc configurations have two cutter rings. The choice of cutter ring configuration depends on factors such as the desired cutting performance and the geological conditions of the tunneling project. Double disc cutters are mainly used in micro-TBMs and in the central area of TBM cutter heads [32].

### 1.3. Material Selection and Heat Treatment

Due to its favorable mechanical properties, hot-work tool steel is often used for the production of disc cutter rings [4,11,27,29–31]. This steel grade has high hardness, toughness, and abrasion resistance and is therefore well suited to the demanding geological and geotechnical conditions of mechanized rock mining. Its high material strength with high fracture toughness enables the steel cutter ring to withstand the high contact stresses and abrasion forces that occur during the cutting process [4,29].

Heat-treatment processes are used to improve the material properties of cutter rings during the manufacturing phase and thus increase their application possibilities. There are several stages of heat treatment in the steel production process. The last stage is the final heat treatment, which is usually carried out in two steps: hardening and tempering. Hardening is the process of preheating, austenitizing, and quenching the cutter ring. The latter involves the rapid cooling of the heated steel, which results in a changed microstructure and therefore a higher hardness. Tempering means reheating at a lower temperature and cooling the cutter ring, which helps improve the toughness of the steel. The general aim of heat treatment is to change the steel's microstructure and properties after a thermal cycle [33]. This leads to improvements in the hardness, toughness, and wear resistance of the disc cutter.

### 1.4. Disc Cutter Wear

Dynamic contact between the disc cutter ring and the excavated rock leads to wear of the cutter ring material. The most common type of wear is normal wear, in which the steel of the cutter ring is worn away evenly. This type of wear is considered optimal as it enables high utilization of the tool [34]. In addition, wear can be predicted during use so that the replacement of worn disc cutters with new ones can be planned.

Five basic macroscopic types of wear can be distinguished in a visual wear analysis. Abrasive wear, tapering/grooving, and mushrooming are considered normal wear. The other two types, bearing blockage and brittle failure, are considered special types of wear. Although special wear types occur less frequently than normal wear types, their effects on TBM tunneling are often much more serious [12,34]. The basic types of disc cutter wear are shown schematically in Figure 1.

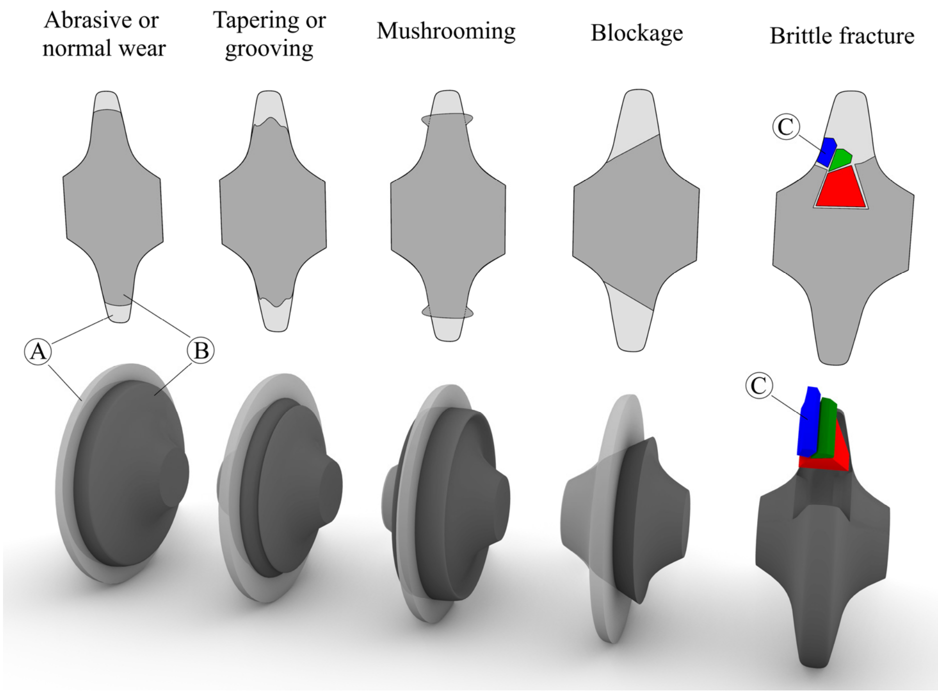


**Figure 1.** Five types of basic disc cutter wear. A and B indicate new (light grey color) and worn disc cutter rings (dark grey color), respectively. C indicates a broken part of the cutter ring due to a brittle fracture. In the lower part of the illustration, only half of the new light-grey-colored cutter ring tip is shown to make the worn cutter ring more visible (adapted from [34]).

Fractures on the disc cutter ring often appear as cutter chipping. Xue et al. [12] investigated this abnormal type of wear and categorized it into four types, granule chipping, patch chipping, primary collapse, and secondary collapse, depending on the size of the damage. Material chipping is shown schematically in Figure 2.

When tunneling with TBMs, it is important to pay attention to the wear of the disc cutters and to carry out appropriate tool maintenance. Failure to replace a disc cutter in a timely manner will accelerate the wear of the surrounding cutters which, in turn, can lead to seal and bearing failures or even damage to the cutter head. About 75–90% of the total consumption of disc cutters is due to normal wear [35,36].

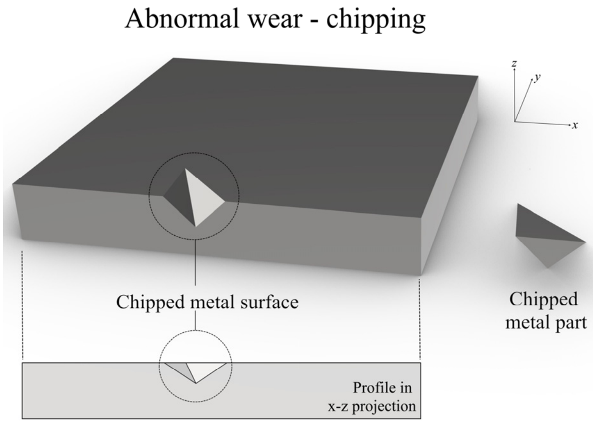


**Figure 2.** Schematic representation of material chipping, one of the abnormal types of wear in TBM disc cutters.

The wear of disc cutters leads to reduced tunneling efficiency. The cost and time required to replace worn disc cutters can account for up to 30% of the total cost and time when excavating in hard rock or rock with high levels of abrasion [5,37]. Therefore, investigating the wear of disc cutters enables better knowledge of the cutting processes and plays an important role in the optimization of TBM tunneling.

The wear of the cutter ring profile is usually measured physically using a special measuring tool: a wear ruler. This allows the amount of profile wear to be measured directly and in millimeters [18,26,36,38]. Wear rulers differ depending on the geometry of the cutter ring profile. This measurement method is suitable for quick assessments of normal wear on the construction site and in the laboratory if the cutter ring is worn evenly around its circumference. In addition, a visual macroscopic inspection is still desirable, especially to detect special types of wear.

### *1.5. Factors Influencing Wear Rate*

The wear of disc cutters must be considered in the context of the tribological system in which three basic components interact: the disc cutter, the rock material, and the environment. From a tribological point of view, the cutting tool is a solid body, the rock material serves as a counter body, and the tunneling conditions form the surrounding environment [39]. Figure 3 is a schematic representation of the tribological system in the case of TBM tunneling. The wear rate of TBM disc cutters is influenced by several factors, including rock properties, tunneling parameters, disc cutter design, and maintenance practices [35,40]. Rock properties such as hardness, abrasiveness, and mineral composition affect wear rate, with harder and more abrasive rock causing faster wear [24,41,42]. Tunneling parameters such as thrust force, torque, cutter head rotation speed, and rate of advance also affect the wear rate, as higher speeds and forces increase contact pressure and friction [43]. The design features of disc cutters, such as shape, size, material composition, and edge geometry, play a role in the wear rate as they affect cutting efficiency and friction [43,44]. Proper maintenance practices, including the timely replacement of worn disc cutters and regular inspections, have a significant impact on wear rate and overall performance. Accurate predictions of disc cutters wear are therefore of great significance to extending cutter life and improving TBM excavation efficiency [45].

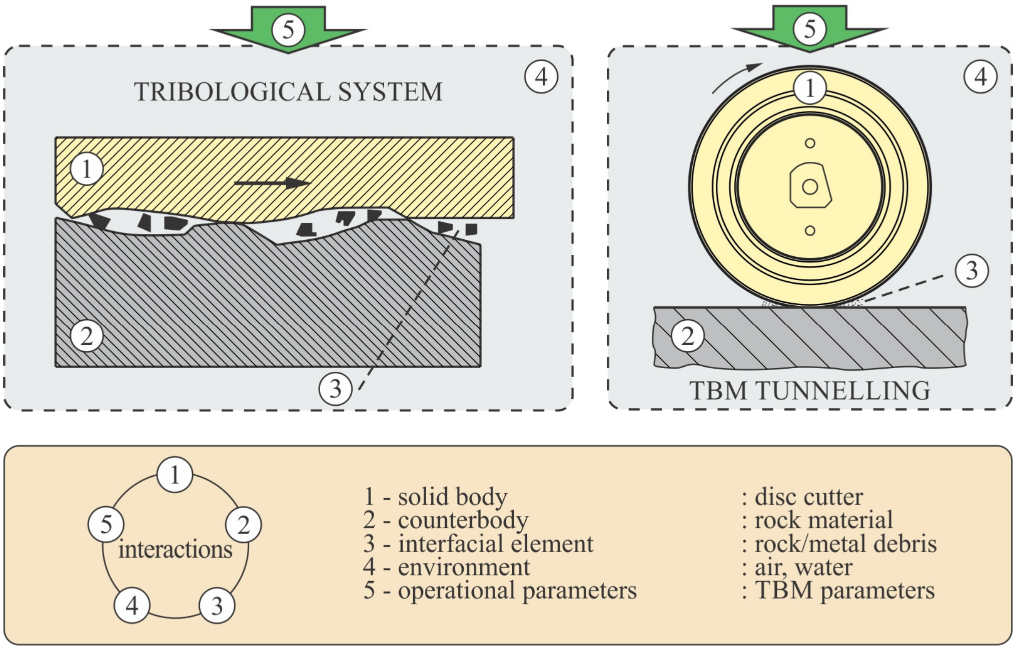


**Figure 3.** Tribological system with key components in the case of TBM tunneling.

### *1.6. Wear Measurement Methods*

Accurate and reliable wear measurements provide valuable insight into the performance and condition of disc cutters, enable proactive maintenance strategies, and optimize cutting efficiency. This section presents several methods for measuring wear that are frequently used in practice or are potentially useful for measurement.

#### 1.6.1. Close-Range Photogrammetry

Photogrammetry, specifically close-range photogrammetry, is a non-contact measurement method that can be used to reconstruct and evaluate the three-dimensional structure and properties of various objects using close-range images. By examining high-resolution images taken from different angles, close-range photogrammetry enables the generation of dense point clouds that represent the spatial distribution of surface points on an object. These point clouds form a basis for the creation of precise 3D models and enable further analysis to extract the relevant parameters and surface features of the object [46].

One of the main advantages of photogrammetry is that it does not require physical contact with the disc cutter. This reduces the risk of the cutter being altered or damaged during the measurement process. In addition, photogrammetry is also known for its cost-effectiveness compared to other sophisticated methods for generating dense point clouds as it relies on standard digital cameras and software tools for data processing. This makes it a more accessible and economically viable option for wear analyses based on 3D models in tunneling.

Until now, researchers had not used close-range photogrammetry to assess the wear of TBM disc cutters. However, this method has been used to assess the wear of other mining tools (e.g., conical picks) [47,48] or to measure the volume of rock fragmentation during TBM tunneling in granite formations [7].

Pawlik et al. [47] aimed to create a photogrammetric 3D model of commercially available conical picks before and after wear. They performed a three-factor experiment on two levels to determine an optimal setting for the scanner system, considering light intensity, the presence of a polarization filter, and the distance to the scanned object. Using an algorithm developed by the authors, they compared a 3D scan of worn samples with a master model and were able to accurately assess the wear rate and condition. The study demonstrates the effectiveness of photogrammetry in assessing the wear of mining equipment and highlights its potential for use in cost-effective regeneration processes. Krauze et al. [48] investigated the wear rate of conical picks using a camera with a 12.2 MP sensor, a photo tent with a built-in light source, and a stepper-motor-driven turntable. Images of the cutting tools were captured from different angles and then processed to create 3D scans before and after use, which enabled the calculation of the volume difference and an evaluation of wear. Cho et al. [7] used photogrammetry to measure the volume of excavated rock after tests using a linear cutting machine (LCM). They used the ShapeMetrix3D system, which generated three-dimensional geometry and digital coordinate data for the cut rock face. This enabled an accurate determination of the cutting volume, which was crucial for calculating the specific energy (SE) and evaluating the cutting performance. The results showed that the photogrammetric determination of the volume of the mined rock enabled the accurate identification of the optimal cutter spacing based on the SE values. This method improved the accuracy of SE estimation and the selection of optimal cutting conditions, resulting in higher efficiency in LCM testing and TBM operation.

Photogrammetry offers several advantages for industrial applications, including the ability to provide detailed information about surface changes in material texture and localized damage in cutting tools. It is a cost-effective method that does not require expensive equipment or extensive training. It also facilitates the rapid scanning and sending of 3D texture files for analysis by wear experts who may not be available on-site. However, photogrammetry also has its limitations. For example, data acquisition must be carried out in a controlled environment to ensure optimal image quality, and special lighting conditions and filters must be taken into account, especially for metallic surfaces. Parameters such as the exposure time, aperture, depth of field, and light sensitivity of the camera can have a significant impact on the suitability of photogrammetric synthesis. Careful attention to these factors is essential to maximize the effectiveness of photogrammetry in industry.

#### 1.6.2. Laser Scanning

Laser scanning is an advanced measurement technique that offers similar possibilities to photogrammetry but with higher precision and greater financial outlay. This method uses laser sensors to capture detailed 3D information on various objects, such as cutting elements made of metal materials, in order to obtain very precise geometric data.

Compared to photogrammetry, laser scanning offers several advantages in terms of precision and accuracy. By directly measuring the distance between the laser sensor and the surface of the cutting element, laser scanning achieves higher accuracy in capturing fine details and intricate wear patterns. The 3D models resulting from laser scanning provide a comprehensive representation of the geometry and wear profiles of the cutting element. However, laser scanning is generally more expensive than photogrammetry. The equipment required for laser scanning, such as laser sensors and associated software, tends to be more specialized and expensive. This higher cost may limit the accessibility of laser scanning for some applications or budget constraints [17,49–51].

In a recent study by Tang et al. [17], 3D laser scanning technology was used to scan and reconstruct the irregular cutting tools of a shield TBM before and after wear. The surface overlap method was then used to compare the reference object (the new cutting tool model) and the test object (the worn cutting tool model). A potential disadvantage of using 3D laser scanning technology for the assessment of the irregular wear of cutting tools is that local depressions with excessive curvature on the tool surface can be difficult to scan, resulting in small holes in the automatically reconstructed model. Zhang et al. [31] investigated the wear characteristics of TBM disc cutters with different degrees of hardness and different blade shapes when cutting various types of rock. Their study focused on analyzing the wear mechanisms, wear depths, and morphology of wear debris based on experimental results of laser scanning microscopy. The main finding of the study was that the wear mechanisms of TBM disc cutter rings varied depending on the hardness of the cutter rings and the type of rock being cut, with microcuts observed in sandstone and rutting deformation followed by microcuts in rust stone. Wear loss and wear depth decreased with increasing hardness of the steel when used in medium-hard and hard rock. However, there is an optimum degree of hardness of the cutter ring for achieving the best wear resistance.

#### 1.6.3. Weighing

Weighing is a simple but effective method for assessing the wear of disc cutters. In this method, new and worn disc cutters are weighed after they are removed from the TBM's cutter head to determine the weight lost due to wear. By comparing the initial and final weights, the wear rate of a disc cutter can be estimated [42,52]. It is important to note that on one hand, this method does not provide insight into the nature of disc cutter wear and therefore cannot serve as an independent method but only in combination with other methods. On the other hand, this method can be very useful and time-saving when it comes to assessing wear as a result of a normal type of wear.

The advantage of weighing is that it is a direct measurement of wear that provides tangible and easy to interpret results. It is a cost-effective and practical technique that does not require complex instrumentation or sophisticated data processing. However, it should be noted that weighing only provides a general measure of wear and does not capture detailed wear patterns or surface topographies. It is therefore recommended to use other methods in addition to weighing to assess wear.

Karami et al. [42] observed the wear of disc cutters during the TBM tunneling of the Kerman water conveyance tunnel. They analyzed the wear of disc cutters based on the mass loss of the cutter rings and compared it with empirical prediction models developed by other researchers. The authors calculated the weighted averages of the rolling mass loss (MR) and volumetric mass loss (MV) of the disc cutters for different geological formations such as flysch, diabase, andesite, and andesitic basalt. By averaging the mass loss values for selected rock layers with similar geological properties, they were able to investigate the effects of rock abrasiveness on the wear of disc cutters. Ma et al. [52] used granite samples from the Beishan area in Gansu Province, China, to conduct wear tests on small disc cutters with different design parameters such as cutter diameter, cutter tip width, and cutter tip shape. In their study, they determined the wear of disc cutters by weighing them. After each test in which the cutting distance of a single disc cutter was 100 m, the cutter was weighed. Using this method, they were able to quantify the wear of small disc cutters and analyze how different cutter shapes affect wear under certain conditions.

#### 1.6.4. Profile Measurement Using a Profile Gauge/Wear Ruler

In addition to the techniques mentioned above, profile measurement using a profile gauge is another frequently used method for assessing the wear of disc cutters. A profile gauge, also known as a wear ruler or measuring template, is a special tool for measuring the profile wear of a disc cutter. The profile gauge consists of a molded template or ruler with a specific contour that corresponds to the original shape of the profile of the disc cutter. By placing the gauge against the worn surface of the cutter, engineers can visually compare the shape and depth of the wear profile with the template.

Profile measurement using a profile gauge is a quick and practical method for assessing the wear condition of disc cutters, especially for visual inspection. It is often used in conjunction with other measurement methods to gain a comprehensive understanding of wear behavior. Several studies [18–21,38,42,53,54] use or mention profile gauges for wear assessment.

Amoun et al. [20] investigated the basic process of disc cutter wear during the construction of the first 6500 m of Tehran Metro Line 7 in soft ground using an earth-pressure-balance TBM. The aim of the study was to understand the effects of soil properties and operating factors on disc cutter wear using a profile gauge. In a study by Liu et al. [19], the extent of disc cutter wear was measured in millimeters using a profile gauge. The worn cutters were properly adjusted to ensure that the difference in cutter ring wear between adjacent cutters was less than 15 mm. This systematic measurement and recording of wear data made it possible to track the wear progression of the cutters and determine when they had reached their allowable wear limit or exhibited abnormal wear that required replacement. Ko and Lee [18] investigated the effect of rock abrasiveness on the wear of disc cutters and slurry discharge pipes in a slurry-shield TBM during tunnel construction in Singapore. The study involved measuring and monitoring the radial wear of disc cutters and the thickness of slurry discharge pipes using specialized tools such as wear rulers and ultrasonic measuring devices. Cerchar abrasivity index (CAI) values were correlated with the wear coefficients of the disc cutters and the carbon steel slurry pipes. These correlations helped the researchers understand the relationship between the degree of weathering of the Bukit Timah granite and the wear rates of the excavation equipment. Barzegari et al. [38] used a special ruler as a measuring tool to measure the depth of normal wear on a cutter. Similarly, Karami et al. [42] used a measuring template to measure the amount of material lost from the tip or cutting edge of a disc cutter.

Although the authors do not explicitly report the disadvantages of using profile gauges, special rulers, or measuring templates to determine the wear of disc cutters, possible limitations such as inaccuracies, subjectivity, and time-consuming manual methods can be considered. These factors can lead to errors, incomplete data, and inconvenience in the measurement process. This emphasizes the importance of exploring advanced and automated measurement systems for greater accuracy.

#### 1.6.5. Profile Measurement with a Sliding Caliper

A caliper, also known as a vernier caliper, is a precision measuring device that provides accurate measurements of wear dimensions, including wear depth, wear width, and wear profile. This technique provides quantitative data on geometric changes in the cutter profile due to wear. The caliper is operated by adjusting its jaws to the wear surface of the disc cutter. The caliper is carefully positioned to measure specific wear dimensions, and the measurements are recorded for further analysis. This technique provides direct and precise measurements that allow for an accurate assessment of wear progression over time.

Researchers and engineers have used calipers to measure the wear of disc cutters due to better disc management. Lan et al. [21] investigated the development and implementation of an online monitoring system for the wear of disc cutters in tunnel-boring machines using an eddy current sensor. They conducted experiments to measure the wear of disc cutters during rock crushing in real time. The researchers used a caliper to measure the actual wear of the disc cutters, which was then compared with wear monitored in real time to analyze any deviations. The caliper was important for obtaining accurate measurements of the disc cutter and to verify the effectiveness of the monitoring system. Zhang et al. [55] analyzed the fracture behavior of TBM disc cutters under different conditions such as rock temperatures and penetration depths. Experimental investigations were conducted to analyze the penetration depth and vertical force exerted by the disc cutter on the rock. They used a caliper to measure the penetration depth of the crater created by the cutter. Yang et al. [56] collected data on the wear condition of 34 disc cutters over 643 days in the Chaoer-to-Xiliao water conveyance tunnel in China. In this study, they used a caliper to manually measure the wear values of the cutters with millimeter accuracy. The caliper was used to record wear data before and after the replacement of the disc cutters. In this way, it was possible to track the progression of wear and the reasons for replacement, e.g., normal wear or other problems such as flat wear, bearing damage, cracks in the cutter ring, and oil leaks.

Although calipers are often used to measure wear values to the nearest millimeter, there are some limitations to their use. One drawback is that human error can occur when measuring manually with calipers, leading to inaccuracies in the data recorded. In addition, manual measurements can be time-consuming and labor-intensive, especially when a large number of measurements are involved. Overall, while calipers are useful tools for many applications, they can also have limitations in terms of their efficiency, accuracy, and suitability for certain types of measurements [57].

#### 1.6.6. Microscopic Inspection

Microscopy can be used to observe various wear mechanisms in steel from which TBM disc cutters are made on a microscopic level. Four different micromechanisms can be observed in the predominant wear mechanism (abrasion): microchipping, microplowing, microfatigue, and microfractures [29]. This optical technique enables the visualization of wear patterns and the identification of specific wear mechanisms on a microscopic level. This method is the only one of the abovementioned methods that requires the extraction and preparation of a cross-sectional metallographic sample of the worn disc cutter.

Microscopy techniques have been used in several studies to investigate the wear of disc cutters. For example, Espallargas et al. [58], Küpferle et al. [29], and Macias et al. [59] carried out a microscopic inspection of the surface of a worn disc cutter to analyze wear characteristics and patterns. Espallargas et al. [58] investigated the influence of corrosion on the abrasive wear of TBM cutter steel in interactions with excavation fluids such as soil conditioners, anti-abrasion additives, and water. They used a scanning electron microscope (SEM; Hitachi S-3400) to study the microstructure of the steel and to examine the topography of the worn material surfaces after the test. Küpferle et al. [29] used a scanning electron microscope (SEM) to visualize and analyze wear mechanisms on a microscopic level, focusing on microchipping, microplowing, microfatigue, and microfracture. An SEM was used to examine the surface of a hot-work tool steel and metal matrix composite (MMC) material to understand how the microstructure and hard phases of the materials affect the wear resistance of TBM disc cutters, chisel tools, reamer tools, and ripper tools. Macias et al. [59] used a focused ion beam (FIB) microscope to cut precise cross-sections from the worn TBM cutter ring samples and mini cutter ring samples without exposing them to air. This method ensured that the samples remained in a controlled environment during the cutting process. The FIB microscope also enabled simultaneous imaging in which the samples were analyzed using a Zeiss Ultra 55 Limited Edition SEM. This comprehensive approach allowed the researchers to examine the microstructure of the samples in detail and gain insight into the mechanisms of cutter ring wear during hard rock tunneling.

Although microscopic observations provide valuable insights into wear mechanisms and material behavior on a small scale, they can also have limitations, such as the need for specialized equipment, time-consuming sample preparation, and potential challenges in interpreting complex interactions at the microstructural level.

#### 1.6.7. Macroscopic Visual Wear Evaluation

The macroscopic visual inspection of disc cutters is the most basic qualitative method for determining wear and is usually performed prior to any techniques that use specialized tools and equipment to measure wear. Basic types of wear can be detected with this method while disc cutters are still installed on the TBM's cutter head [34].

Based on a visual inspection, the wear of disc cutters can generally be classified into normal wear and abnormal wear with the corresponding subcategories [36].

Many researchers who have studied the wear of disc cutters have also performed macroscopic wear evaluations [12,19,34,38,53,60]. Xue et al. [12] conducted field research to categorize the chipping patterns of disc cutters through macroscopic observations of failure patterns and fracture surface features. Their work made an important contribution to understanding the mechanism of chipping and its morphological features through visual observations. Liu et al. [19] visually depicted the extent of cutter ring wear in different types of TBM disc cutters along two different tunnel sections. Similarly, Ellecosta et al. [34] outlined five basic macroscopic wear types for cutter rings observed in TBM tunneling. Barzegari et al. [38] emphasized the importance of macroscopic observations in identifying abnormal wear patterns such as the cracking, spalling, mushrooming, and chipping of cutter rings. They discussed the importance of these observations in detecting wear irregularities. Agrawal et al. [53] analyzed the wear patterns and characteristics of disc cutters at a macroscopic level to understand the effects of various parameters such as rock strength, abrasiveness, machine parameters (thrust force, torque, etc.), and operating conditions on cutter wear and penetration rate in tunnel construction. Furthermore, Jin et al. [60] used a TBM case study in Shenzhen to determine the failure modes of disc cutters through visual observation. Their study showed that about 91.71% of cutter tool failures were due to uniform wear, suggesting that this is the main cause of failure.

Based on the information provided by these authors, who focus primarily on describing and analyzing different macroscopic types of wear in TBM hard-rock drilling, the drawbacks or limitations of their observations were explicitly not addressed. However, it is important to point out that there may be limitations or drawbacks in any study, such as possible biases in observations, variations in field conditions, or problems in generalizing the results. Further details or a comprehensive analysis would be required to identify the possible drawbacks of these macroscopic observations.

### *1.7. The Wear Method Selection*

Each of the methods for measuring or evaluating the wear of disc cutters has some advantages and disadvantages. It would be pointless to determine which method is better than the others as they are all suitable for a specific purpose. The wear methods are generally differentiated by four influencing factors which are listed in Table 1:

- Measuring and/or processing equipment;
- Execution time;
- Cost of equipment and personnel;
- Location of measurement or evaluation.

The accuracy of each method depends on the accuracy of the equipment used and the operator performing the measurements or evaluation. The choice of wear assessment method depends on the purpose. Experience shows that in general, a combination of several methods simultaneously provides the best results and a comprehensive insight into the wear of disc cutters.

**Table 1.** Summary of frequently used methods for the high-precision measurement and evaluation of the wear of disc cutters with a comparison according to the most important influencing factors.

| Method | Equipment | Time Expenditure (Fast/Medium/Slow) | Estimated Cost (Low/Medium/High) |
|---|---|---|---|
| Close-range photogrammetry | digital camera<br>accessories for photography<br>computer software | slow | medium |
| Laser scanning | laser scanner<br>accessories for scanning<br>computer software | slow | high |
| Weighing | weighing scale | fast | low |
| Profile gauge | wear ruler | fast | low |
| Caliper | digital or mechanical caliper | medium | low |
| Numerical modeling | equipment for laboratory testing of material (steel and rock)<br>computer software | slow | high |
| Microscopic inspection | microscope<br>equipment for obtaining metallographic cross-sections | slow | high |
| Macroscopic inspection | / | fast | low |

## 2. Materials and Methods

### *2.1. Investigation of a Worn Double Disc Cutter*

In this study, the wear of a double disc cutter was investigated. A disc cutter with a diameter of 330.2 mm was manufactured from the hot-work tool steel H13. A technical drawing showing the corresponding geometry of the new double disc cutter is shown in Figure 4. Observations were made using a worn double disc cutter after it had been removed from an MTBM's cutter head. The material in which the double disc cutter was used for microtunneling consisted mainly of alternating layers of partially fractured sandstone and claystone with fine-to-medium grain sizes.

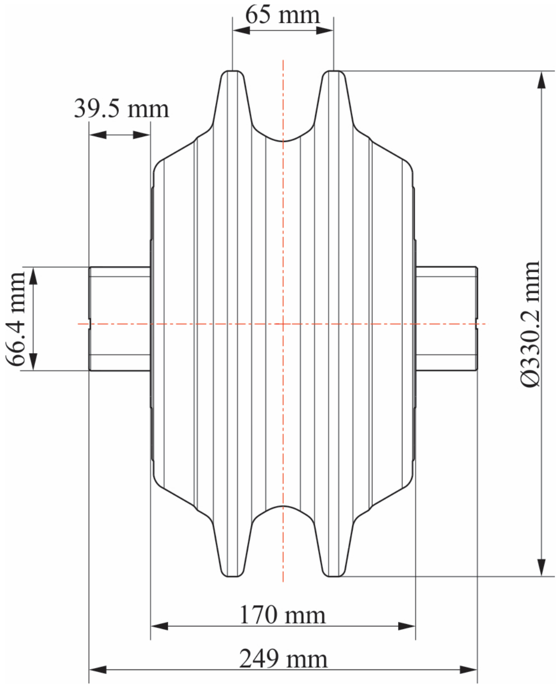


**Figure 4.** Technical drawing of the new double disc cutter.

### *2.2. Planning and Implementation of Wear Measurements*

In this study, four different measurement methods were used to evaluate the wear of the double disc cutter. These were a macroscopic visual inspection, profile measurement with a caliper, weighing, and close-range photogrammetry. All measurements were carried out in a laboratory under the same environmental conditions.

#### 2.2.1. Macroscopic Visual Inspection

A worn double disc cutter was subjected to a detailed visual inspection and photographed to identify the type of wear. The disc cutter was placed on a specially designed turntable that allowed for rotation around its vertical axis to perform a comprehensive macro-level examination. First, the disc cutter was inspected from one side up and then from the other side up to examine the entire surface. After the visual inspection, the predominant type of wear on the worn double disc cutter and the presence of other types of wear were determined. In such cases, non-dominant types of wear usually only occur to a small extent.

#### 2.2.2. Measuring the Profile with a Caliper

The diameter of the worn double disc cutter was measured using a Mitutoyo vernier caliper with a capacity of 500 mm and a resolution of 0.01 mm. Due to the position of the disc cutter during the measurements, the two rings of the disc cutter are referred to as top and bottom cutter rings. Before starting the measurements, the disc cutter was divided into 18 profiles that ran through the center of its axis of rotation. The profiles were evenly spaced at 10° intervals. The profiles were labeled on both rings of the disc cutter with short white line and numbers from 0 to 17 (18 profiles in total). The labeled profiles on the upper cutter ring (top) of the double disc cutter are shown in Figure 5a. The diameter of each of the 18 profiles was measured with a caliper with an accuracy of 0.01 mm (Figure 5b). When measuring the diameter, special care was taken to ensure that the caliper jaws were always perpendicular to the measured distance when reading the diameter. This was achieved by placing the caliper beam on the shaft of the disc cutter, which has a flat surface and is perpendicular to the axis of the disc cutter. The diameter measurements were taken separately on both cutter rings (top and bottom) of the double disc cutter. In this way, 18 diameter measurements were taken for the upper cutter ring (top), and 18 measurements were taken for the lower cutter ring (bottom). All measurements were carried out under the same environmental conditions in the same laboratory room at a constant temperature.

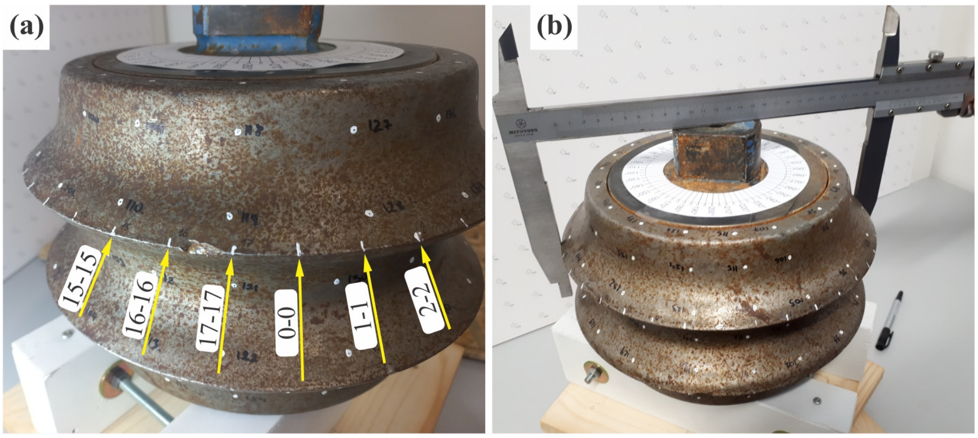


**Figure 5.** Measuring the diameter with a manual caliper. (**a**) Labeled profiles on the upper cutter ring (top); (**b**) the method of manually measuring the diameter with a caliper. Note that the white dots on the surface of the disc cutter were used for close-range photogrammetry.

#### 2.2.3. Weighing

The mass of the worn double disc cutter was measured using a Kern HCB 200K100 (KERN & SOHN GmbH, Balingen, Germany) digital hanging scale with a capacity of 200 kg and a reproducibility of 0.1 kg. Before weighing the disc cutter, a special steel eye bolt that fit into the shaft thread of the disc cutter was prepared and weighed. The eye bolt was needed to attach the scale with the hook to the disc cutter. Then, the disc cutter with the mounted hanging scale was lifted with a special manual hanging crane, as shown in Figure 6, and the measured total mass was read on the hanging scale. At the end, the mass of the eye bolt was subtracted from the total mass. The masses of the worn disc cutter and the new disc cutter were compared, and the mass loss was determined.

#### 2.2.4. Close-Range Photogrammetry

To obtain a dense point cloud and three-dimensional model of the worn double disc cutter, a close-range photogrammetry technique was used.

First, a plastic background plate with 375 printed targets was created, with the targets or markers serving as georeferencing points. The plate, which measured 100 × 60 cm, was flat and firm enough not to deform, i.e., all points were in the same plane. It also stood on a metal base, which ensured the verticality of the plate. The markers were placed in a grid with equal spacing in the x and y directions, as shown in Figure 7. The coordinates of the markers were then calculated based on an arbitrarily chosen marker representing the starting point of the plane coordinate system ($z = 0$) and the fact that the markers were 40 mm apart in both the x- and y-axes.

**Figure 6.** Weighing the worn disc cutter using a digital hanging scale.

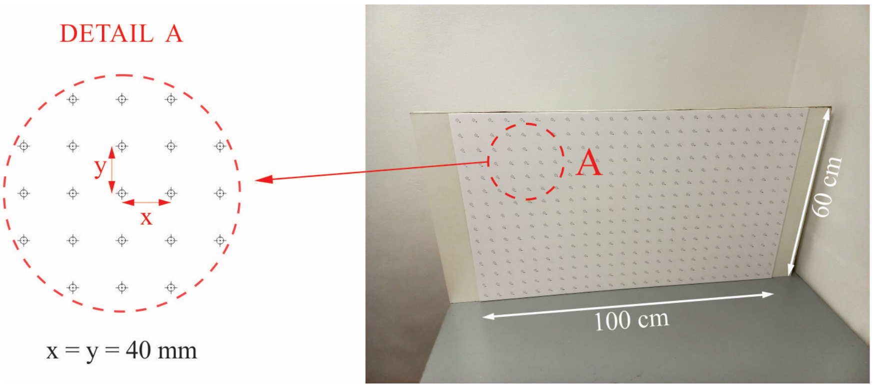


**Figure 7.** A background plate with targets used for close-range photogrammetry of the worn double disc cutter.

Secondly, a special turntable was built to rotate a double disc cutter around its vertical axis. A base was used to place the double disc cutter in a stable position directly above the center of the turntable. This ensured a constant distance between the camera and the photogrammetric object at all angles of rotation around the vertical axis.

After the cutter was placed on the base, it was covered with a dense network of 162 numbered points (markers) that were drawn over the entire surface. The markers serve as control points and tie points to achieve the highest possible accuracy in the photogrammetric reconstruction. In addition, a 360° measuring circle (protractor) was placed on the upper part of the disc cutter to mark 18 sectors with an angle of 20°. At each sector boundary, nine points were marked at approximately the same locations in the vertical direction, as shown in Figure 8.

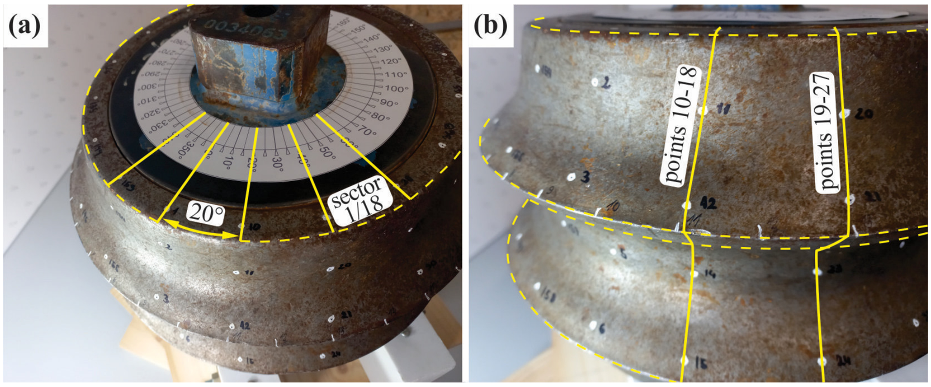


**Figure 8.** Marker points on the disc cutter's surface. (**a**) Sectors on the upper cutter ring; (**b**) detail of a sector with marker points on the boundary lines.

The upper (top) and lower (bottom) parts of the double disc cutter were photographed separately using an NEX-5 camera (Sony Co., Minato City, Tokyo, Japan) equipped with an E-mount 16 mm f/2.8 lens, which has a resolution of 4592 × 2576 pixels and a pixel size of 5.48 × 5.48 µm. Camera calibration was carefully performed using a checkerboard pattern to ensure the precise determination of internal parameters such as the focal length, optical center, and distortion coefficients of the lens.

Photography was carried out in such a way that 11 photos were taken in each shooting position as the camera was mounted on a tripod with a special slider that allowed the camera to be moved horizontally and in the millimeter range. In this way, a total of 198 photos were taken for each side of the disc cutter (the upper and lower parts). To achieve the precise rotation of the disc around its vertical axis, a laser beam was used, as shown schematically in Figure 9.

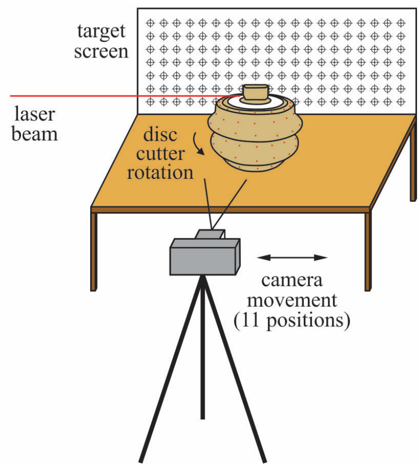


**Figure 9.** Disc cutter photography (schematic).

The photos were then processed using Agisoft Metashape 1.6.3 software. To improve accuracy and resolution while maintaining finer detail, ultra-high-quality and aggressive filtering techniques were used during processing. This ensured that only the most accurate and relevant points were retained. The top and bottom point clouds of the disc cutter were created separately and then merged into a final dense, high-resolution cloud.

The entire process, from image alignment to the creation of a dense point cloud and final model, took 1 h and 47 min. The photogrammetric analysis was performed on a high-performance PC equipped with 64 GB RAM, an i9-10900F 2.8 GHz processor, and an NVIDIA Quadro RTX 5000 GPU graphics card with 16 GB GDDR6 memory.

After creating a three-dimensional model of the worn disc cutter, the worn profile of the disc cutter was created using Rhinoceros 7 software and compared to the original profile. Furthermore, the volume and mass of the worn disc cutter were calculated using the 3D model and compared with the mass loss determined by weighing.

All photographs of the disc cutter taken during the close-range photogrammetry process were taken in the same room and under the same lighting conditions.

### 2.3. Cost Analysis of the Methods Used

A comprehensive cost analysis of different methods for evaluating the wear of disc cutters was carried out and is shown in Table 2. The initial investment, the time required for the wear assessment, and the complexity of the measurement methods were evaluated to gain an insight into the cost efficiency and practicability of each method.

**Table 2.** Comparison of the cost and complexity of methods for assessing the wear of a dis cutter.

| Method | Initial Investment | Required Time for Wear Assessment | Complexity |
|---|---|---|---|
| Macroscopic inspection | EUR 0.0 | 1 h | Low |
| Caliper | EUR 800 | 2 h * | Low |
| Weighing | EUR 170 | 1 h | Low |
| Close-range photogrammetry | EUR 650–EUR 3000 ** | 15 h | High |

* The time required for the wear assessment with the caliper method includes the measurement of 18 profiles of cutter rings on both sides of the double disc cutter with the caliper tool. ** The price, which includes the purchase of high-performance computer equipment and photography accessories for photogrammetric analysis.

The price range for photogrammetry includes the purchase of a low-cost camera, software, and, if needed, the purchase of high-performance computer equipment for a photogrammetric analysis. Additionally, the caliper method involves purchasing a caliper, while the weighing method entails buying a digital scale for weight measurements. No running costs were incurred, and labor costs are not included in the analysis as these may vary depending on the hourly rate of the measurement personnel.

All measurements can be performed relatively quickly, within an hour or two, except for photogrammetry, for which the setup and execution take about 5 h. The photogrammetric analysis took approximately 15 h, including pre-processing, for which the time depends mainly on the number of photos and reference and control points, taking about 8 h, and photogrammetric processing, which took about 2 h. It is worth noting that the pre-processing time can be shortened if coded markers are used for reference and/or control points which the software detects automatically on each photo. Additionally, the photogrammetric processing time depends on the performance of the computer equipment.

The complexity of these methods varies depending on the level of expertise required, the equipment needed, and the intricacy of the procedures involved. The macroscopic inspection method is relatively straightforward, requiring visual observation skills, but may lack precision due to its subjective nature. The caliper method involves using a simple measuring tool and basic mathematical calculations, making it relatively easy to perform with minimal training. Weighing involves operating a digital scale and recording measurements accurately, which is generally uncomplicated. However, close-range photogrammetry introduces a higher level of complexity. It necessitates proficiency in photographic techniques, software operation, and potentially computer hardware setup. Furthermore, the analysis stage, particularly pre-processing and processing, demands meticulous attention to detail and may require advanced knowledge of photogrammetric principles. Despite this complexity, advances in technology and software automation can mitigate some of the challenges associated with photogrammetry, enhancing its accessibility and usability over time.

# 3. Results and Discussion

## 3.1. Macroscopic Visual Inspection

After a detailed macroscopic visual inspection, it was concluded that the main type of wear on the double disc cutter is normal abrasive wear. The profiles of both disc cutter rings are evenly worn and have the same cross-section. There is also evidence of some localized damage to the steel material, known as cutter chipping. Two of these chips are medium-sized and have sharp edges. One is about 25 mm long and 1 mm deep (bottom cutter ring) and the other is about 15 mm long and 2 mm deep (top cutter ring). The medium-sized localized damage is shown in Figure 10. A similar chipping of cutters, referred to as a "brittle fracture", has been found in studies from other researchers [12,38,59]. The reason for a brittle fracture can be excessive overloading of the tool or material imperfections caused by the steel manufacturing process. The effect of brittle material removal can be reduced by increasing the toughness of the steel. However, this would lead to a higher wear rate as hardness generally decreases with increasing toughness. The material properties must therefore be adapted with regard to the prevailing wear mechanism [34]. There are also some examples of minor localized damage on both cutter rings of double disc cutter, measuring up to a length of about 5 mm and a depth of 1 mm.

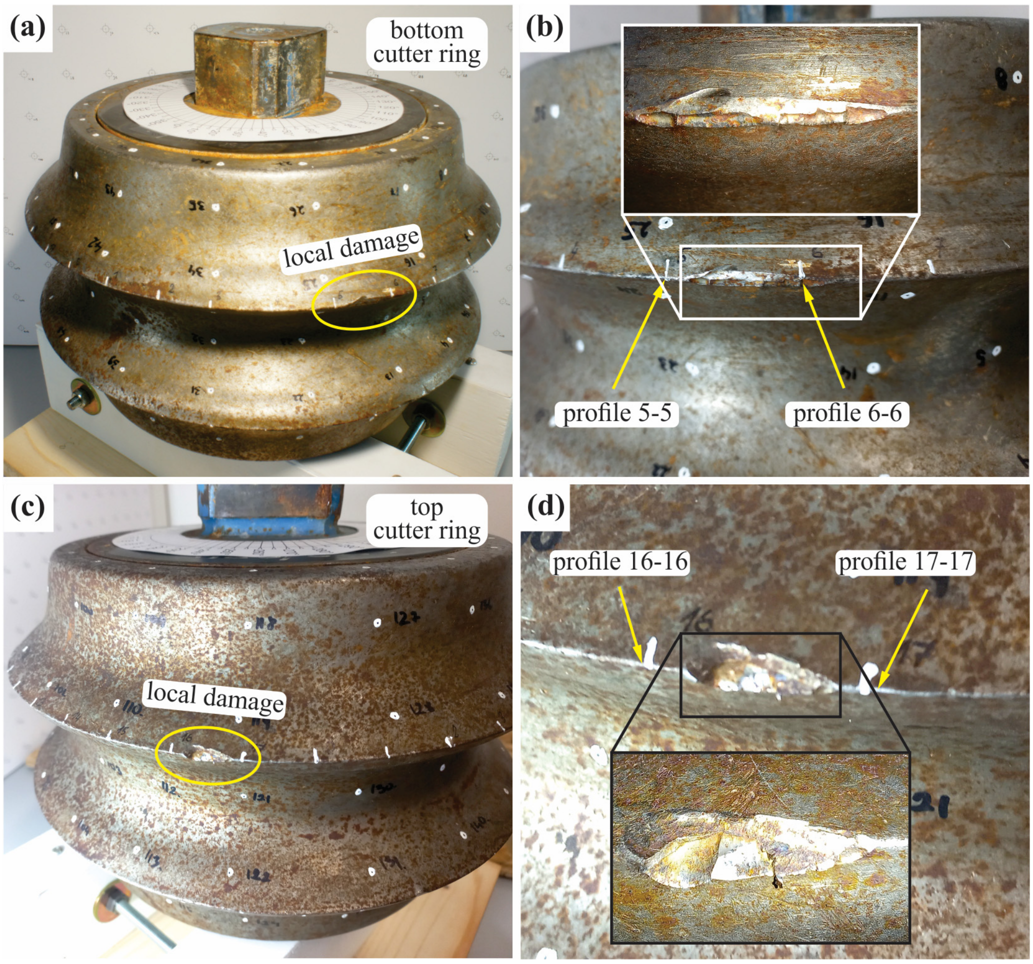


**Figure 10.** Local damages on the lower (bottom) and upper (top) cutter ring surface. (**a**) Area of localized damage on the bottom cutter ring of the double disc cutter, (**b**) enlarged view of the damage between profiles 5–5 and 6–6, (**c**) area of localized damage on the upper (top) cutter ring of the double disc cutter, and (**d**) enlarged view of the damage between profiles 16–16 and 17–17.

Thus, the worn disc cutter examined in this study exhibits both normal and special types of wear, according to the classification published by Ellecosta et al. [34]. However, it should be mentioned that most of the wear belongs to the normal type of wear, i.e., abrasive wear. This type of wear is considered optimal for tunneling with TBM technology as it allows one to predict possible wear and, consequently, the maintenance and schedule of tunnel construction.

### 3.2. Measuring the Profile with a Caliper

The results shown in Table 3 were obtained by manually measuring the diameter of the upper (top) and lower (bottom) cutter rings of the double disc cutter. A total of 36 measurements were taken. The average value of the diameter of the upper (top) cutter ring, which considers all 18 profiles, is 274.096 mm. The maximum value of the measured diameter is 274.160 mm, the minimum value is 274.020 mm. The standard deviation is ±0.042 mm. For the lower (bottom) cutter ring, the average value is 274.201 mm, the maximum value is 274.260 mm, and the minimum value of the measured diameter is 273.840 mm. The standard deviation is ±0.095 mm. The scatter of the measured values around the mean value (dispersion) is higher on the lower (bottom) cutter ring of the disc cutter ($\sigma^2$ = 0.009). The main reason for this is obviously the measurement on profile 6–6, where there is medium-sized localized damage on the surface of the disc cutter.

**Table 3.** Manual diameter measurements obtained using a vernier caliper for the upper (top) and lower (bottom) cutter rings for 18 profiles.

| Profile (/) | Degree Circle (°) | Top Cutter Ring Diameter (mm) | Bottom Cutter Ring Diameter (mm) |
|---|---|---|---|
| 0–0 | 0–180 | 274.12 | 274.22 |
| 1–1 | 10–190 | 274.12 | 274.22 |
| 2–2 | 20–200 | 274.12 | 274.12 |
| 3–3 | 30–210 | 274.02 | 274.22 |
| 4–4 | 40–220 | 274.04 | 274.22 |
| 5–5 | 50–230 | 274.04 | 274.14 |
| 6–6 | 60–240 | 274.10 | 273.84 |
| 7–7 | 70–250 | 274.14 | 274.24 |
| 8–8 | 80–260 | 274.16 | 274.22 |
| 9–9 | 90–270 | 274.14 | 274.26 |
| 10–10 | 100–280 | 274.12 | 274.22 |
| 11–11 | 110–290 | 274.04 | 274.24 |
| 12–12 | 120–300 | 274.02 | 274.22 |
| 13–13 | 130–310 | 274.10 | 274.24 |
| 14–14 | 140–320 | 274.10 | 274.24 |
| 15–15 | 150–330 | 274.12 | 274.24 |
| 16–16 | 160–340 | 274.10 | 274.26 |
| 17–17 | 170–350 | 274.12 | 274.26 |

Considering both sides of the double disc cutter, the average total diameter is 274.148 mm (±0.0946 mm).

The diagram in Figure 11 shows the measured diameters for the upper (top) and lower (bottom) cutter ring according to the profile of the disc cutter. The reduction in diameter due to medium-sized localized damage on the lower profile 6–6 is clearly visible.

In general, there are no major deviations in the manual measurements of the disc cutter ring diameter by the individual profiles. This indicates that both cutter rings were worn relatively evenly during their use on the micro-TBM's cutter head, which also applies to the entire double disc cutter. According to the measured diameters of the cutter rings, there are several smaller instances of localized damage and one larger one. This can be determined without a prior macroscopic visual inspection of the disc cutter. A deviation in the diameter of a particular profile or several profiles from the neighboring profiles is an indication of the highly probable possibility of the presence of localized damage. According to the diameter measurements, the largest localized wear damage is present on the lower (bottom) cutter ring. A diameter of 273.840 mm was measured for profile 6–6. This diameter deviates 0.361 mm from the average value of the diameter measurements on the lower (bottom) cutter ring. The diameter on the neighboring profile 5–5 is 274.140 mm, and on profile 7–7, is 274.240 mm. If there was localized damage in the form of removed material (chipping) between the labeled profiles on the cutter ring, this could not be detected by measuring the diameter along the profile. According to the photos taken during the macroscopic visual inspection, there are several such cases: obvious damage between profiles 16–16 and 17–17 on the upper cutter ring and some minor damage of a small size.

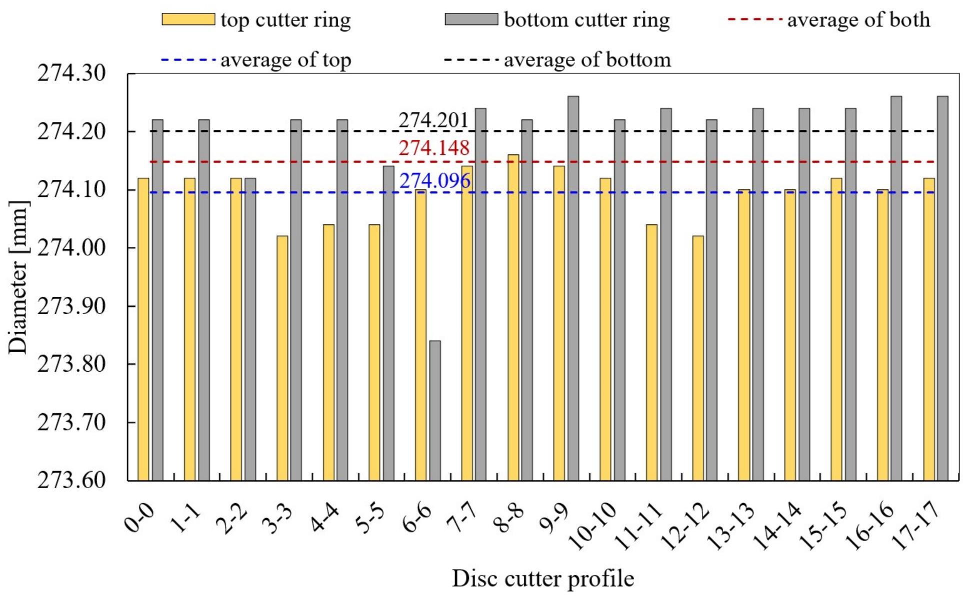


**Figure 11.** Diagram showing the diameters of the upper (yellow) and lower (grey) cutter rings of the double disc cutter measured using a caliper.

The original diameter of the new double disc cutter is 330.2 mm (13″). The worn diameter of the disc cutter is 274.148 mm if the average value of both cutter rings is considered. The original diameter was reduced by 56.052 mm or 17% due to abrasive wear. In other words, the profile of the disc cutter was reduced by an average of 28.026 mm. The original diameter and the worn diameter with the corresponding worn surface of the disc cutter are shown schematically in Figure 12.

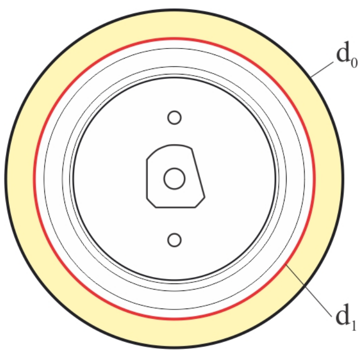


**Figure 12.** Original ($d_0$) and average worn ($d_1$) diameters of the double disc cutter. The worn surface is colored yellow.

### 3.3. Weighing

The original disc cutter had a mass of 67 kg. The mass of the worn disc cutter, measured using a hanging scale, is 55.2 kg. The mass loss determined by weighing is therefore 11.8 kg. Given the density of steel $\varrho_S$ = 7.85 kg/dm$^3$, the volume loss of the worn disc cutter, determined by weight measurement, is 1.503 dm$^3$.

Weighing as a measurement method for assessing the wear of a disc cutter is recommended in combination with other methods as it alone does not allow satisfactory conclusions to be drawn about the type of wear except in the case of normal/uniform wear. However, this type of measurement saves a significant amount of time.

If the change in a disc cutter's profile during normal/abrasive wear is known or predicted from previous TBM projects or studies, weighing the worn disc cutter can provide results for the worn diameter or profile without the need for measurements obtained by other contact or non-contact techniques.

### 3.4. Close-Range Photogrammetry

A dense point cloud with 47,742,682 points was created by processing 396 photos, 16 selected reference points (visible in all camera positions), and 129 control points. The resulting 3D model consisted of a mesh with 9,548,536 faces and 4,775,132 vertices, as shown in Figure 13. The calculated RMS (Root Mean Square) reprojection error of 0.0802754 (0.538642 pixels) shows a precise alignment between the reconstructed 3D points and their corresponding 2D positions in the images and confirms the high quality and accuracy of the reconstruction.

**Figure 13.** A 3D model of a worn disc cutter, created in Agisoft Metashape 1.6.3 software.

Rhinoceros 7 software was used to create a worn cross-section on profile 4–4 of the double disc cutter from the dense point cloud and compare it with the original cross-section. Figure 14 shows constructions of the original profile and the worn profile, wherein the geometry of the worn profile is clearly recognizable.

The worn surface of the disc cutter can be seen in Figure 15, in which a detailed view of the original and the worn profiles of the cutter ring tip can be seen. It was not possible to physically obtain the new disc cutter, so the original profile is based on the original technical drawing. The profile of a worn cutter ring tip differs considerably from its original profile. The cyclically loaded contact between steel and rock material during the rolling motion of the disc cutter leads to fatigue of the steel, which manifests itself in the formation of microcracks and the gradual removal of the steel material from the disc cutter ring. Due to its constant contact with the drilled rock, the tip of the disc cutter is exposed to a high level of material removal.

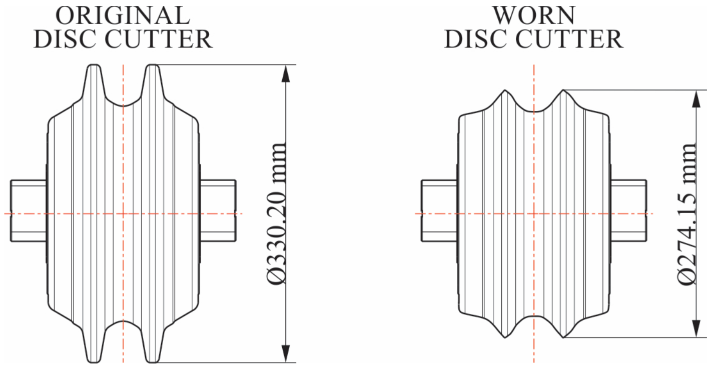


**Figure 14.** Original cross-section (Ø 330.2 mm) and worn cross-section (Ø 274.2 mm) of the double disc cutter.

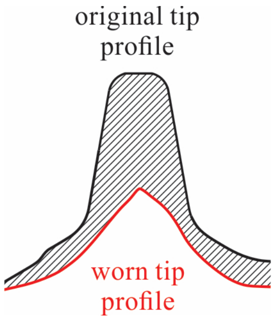


**Figure 15.** Detailed view of the original profile (top—black) and the worn profile (bottom—red) of cutter ring tip reconstructed from the point cloud. The worn surface of the profile is hatched.

The profiles of the original and worn disc cutters were further used to create 3D models of the original and worn double disc cutters. For the sake of simplicity, the models were constructed without the shaft of the disc cutter, as this is unnecessary for the volume comparison as it remains unchanged and is not subject to wear. It was also assumed that the worn profile, as shown in Figure 15, is the same throughout the disc cutter. The volumes of the original and the worn disc cutter were then determined. The difference between the two volumes (original and worn) is 1.4548 dm$^3$. Considering the density of steel (7.85 kg/dm$^3$), the calculated mass loss is therefore 11.42 kg. The comparison between the mass loss determined by weighing (11.8 kg) and the mass loss determined by three-dimensional modeling from the point cloud shows that both values are very comparable and lie within a 4% deviation. Three-dimensional models of the original and the worn disc cutters are shown in Figure 16.

In general, the wear of the double disc cutter used in this study was normal or uniform. This type of wear is desirable in tunneling with TBM technology as it allows for the most efficient use of the cutting tool. In addition, normal wear ensures a predictable drilling process and provides a possible plan for replacing worn disc cutters. Normal disc wear is generally the most common type of wear in TBM tunneling and occurs in about 75% to 90% of cases [35,40,61].

Looking at the original and the worn profiles of the disc cutter used in this study (Figure 15), the contact pressure on the disc cutter ring appears to increase during wear with the same tunneling parameters and the same geology. The width of the original ring tip of the disc cutter is much greater than the width of the worn ring tip. According to Hertz's theory [62–64] of contact pressures, this means that the disc cutter is exposed to ever greater contact stresses with increasing wear. This can be claimed for the case study in this research, in which the wear of the disc cutter was uniform.

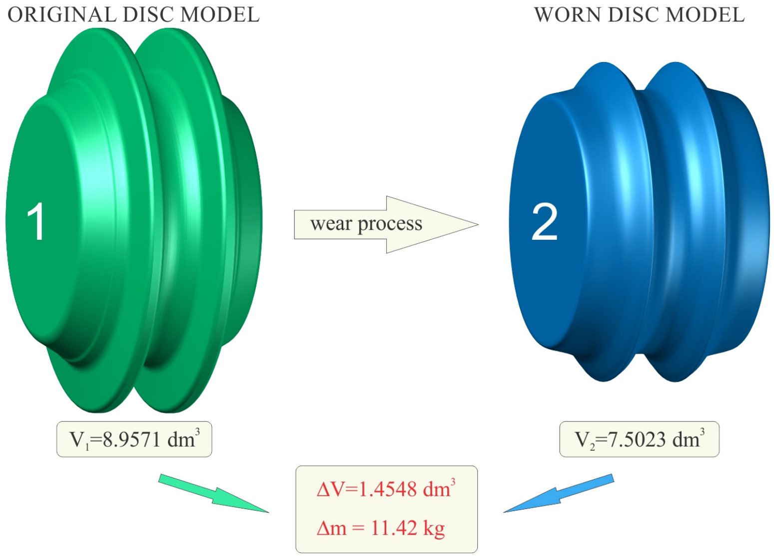


**Figure 16.** A 3D model of an original (No. 1) disc cutter and a worn (No. 2) double disc cutter created based on the original and worn profiles with calculated volume and mass losses due to wear.

## 4. Conclusions

In this article, the wear of an MTBM disc cutter was evaluated using four different measurement methods. Using macroscopic visual inspection, profile measurement with a caliper, weighing, and close-range photogrammetry, various approaches for evaluating the wear of the double disc cutter were tested. The aim of this study was to compare different methods of assessing wear and to construct the profile of a worn double disc cutter based on a point cloud obtained from close-range photogrammetry measurements. The main conclusions from the comparison of the different wear assessment methods can be summarized as follows:

(a) During the macroscopic visual inspection, the type of wear on the double disc cutter was defined as normal abrasive wear with some localized cutter chipping. In general, macroscopic visual inspection is a very suitable method for determining the wear type of TBM disc cutters. It is a time-saving method that does not require any special equipment and can be performed even if the disc cutters are still installed on the TBM cutter head. It is recommended to be performed in addition to all other methods.

(b) Profile measurements were taken every 10° on both sides of the disc cutter ring (top and bottom) using a manual vernier caliper. This method is more time-consuming than the previous one and requires a caliper with sufficient capacity that is larger than the diameter of the disc cutter. The caliper method provides information on whether the wear is uniform or not. It can also detect some localized defects that manifest themselves as plastic deformation or material loss.

(c) The mass loss of the disc cutter was determined by weighing it using a digital hanging scale. This method is easy to perform and requires a scale with sufficient capacity and an additional tool such as a crane to lift the disc cutter. This method is recommended similar to (a), which is performed in addition to the other methods.

(d) Close-range photogrammetry was used to create a three-dimensional point cloud of the worn disc cutter. This method is the only one in this study that allows for the creation of a 3D model on which measurements and comparisons with other disc cutters can later be made. This method was also used to create a worn profile of the disc cutter ring and compare it with the original profile. On one hand, close-range photogrammetry requires a lot of time and specialized equipment, such as a suitable camera and computer equipment, but on the other hand, it offers the possibility of achieving the same results as the methods from (a) to (c). The assessment of wear achieved using the close-range photogrammetry method is consistent with the measurements from the other methods used in this study.

Among the various methods for evaluating and measuring the wear of TBM disc cutters, the selection of a method depends on the required precision, the available measuring time and location, the accessible equipment, and the qualification of the measuring personnel. For a comprehensive investigation of the wear of disc cutters, several methods should be carried out simultaneously in order to achieve the best results.

The measurement methods presented in this study have a significant impact on engineering applications. By integrating different techniques such as photogrammetry, caliper measurements, weighing, and visual inspection, engineers can develop proactive maintenance strategies, optimize cutting efficiency, perform comparative wear analyses under different geological conditions, validate numerical models, and explore innovative wear monitoring systems for disc cutters. Furthermore, these methods offer practical solutions for real-world applications, considering the amount of time they take, the equipment needed, and how well personnel can be trained. For example, establishing a database of worn disc cutters would allow for the systematic monitoring of disc cutter wear under various tunnel conditions. This would facilitate data-driven decision making and enable the development of targeted maintenance strategies. Furthermore, with access to such data, material development for disc cutters could be optimized by focusing on the most common forms of wear. By adjusting material properties to reduce the frequency of these wear patterns, engineers can improve the durability and performance of disc cutters, ultimately increasing the overall efficiency of tunnel construction.

Although this study is based on established methods, a novel application of close-range photogrammetry specifically tailored to TBM disc cutters is presented. As far as the authors are aware, this precise method for quantifying the wear of disc cutters by creating a dense point cloud and a three-dimensional model and then comparing it with reference profiles has not yet been used in this context before. This innovative approach enables a detailed analysis of volume and mass losses and provides a comprehensive insight into the extent of wear of the disc cutter.

As this study presents the results of a single case study, it is important to recognize that the generalizability of these results may require further validation and testing in a broader range of conditions. Although this research provides valuable insight and forms a basis for evaluating the wear of disc cutters, it may not be directly applicable to all TBM operations, geological conditions, and cutter materials. In order to improve the generalizability of the results presented in this study, future investigations could repeat this study on several TBM projects with different geological formations, operating parameters, and disc cutter materials. Comparative analyses and validation in different scenarios could provide a more solid understanding of the wear patterns and evaluation methods for disc cutters and ensure broader applicability and the generalizability of the results.

The aim of future work is to build on the results of this study to investigate other worn TBM disc cutters and comprehensively compare their wear patterns on a larger scale, considering geological variations and TBM boring parameters.

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