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A Digital Twin-Driven Approach for Detecting Overbreak and Underbreak in Drill-and-Blast Tunnels

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Abstract

This study presents a computational workflow for detecting overbreak and underbreak in drill-and-blast tunnels, grounded in the principles of Digital Twin technology, with the objective of enhancing blasting quality control during tunnel construction. Utilizing 3D laser scanning technology, a 3D model of the real-world tunnel is constructed and integrated with the design model for comparative analysis. The differences in the contours of both models are computed, facilitating the automated assessment of overbreak and underbreak volumes in blasting sections. The specific workflow encompasses data acquisition, point cloud processing, model construction and optimization, as well as model integration and analysis, thereby establishing an efficient and precise system for detecting overbreak and underbreak. In comparison to traditional manual section measurement methods, the proposed approach not only significantly reduces labor workload but also substantially enhances detection accuracy. This technology offers reliable technical support for tunnel blasting quality assessment, effectively addressing the challenges of high labor input in drill-and-blast tunnel construction.

1 Introduction

Drill-and-blast excavation is the most widely employed method in mountain tunnel construction, owing to its high adaptability and cost-effectiveness, especially in the construction of long-distance tunnels in complex geological conditions. However, mountain tunnel projects often involve the

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simultaneous construction of multiple tunnels over extensive distances, presenting considerable challenges for the efficient management of tunnel groups. Existing quality control technologies for drill-and-blast tunnel construction often fail to meet the required standards of efficiency and precision. Coupled with the uncertainty of geological conditions and the subjectivity of manual operations, this frequently results in overbreak and underbreak.

Overbreak and underbreak refer to the deviations between the actual excavation profile and the design tunnel profile. Overbreak occurs when the excavation profile exceeds the design boundary, whereas underbreak occurs when the excavation profile falls short of the design boundary. The primary causes of these deviations include conservative blasting parameters, unpredictable geological conditions, and variability in manual operations. Blasting designs often employ conservative parameters to ensure safety, limiting the ability to control excavation boundaries. Moreover, the drilling location and explosive charge placement in drill-and-blast methods are highly dependent on the operators' subjective judgment, with variations in their technical skill and experience impacting the consistency of the results. Furthermore, the inherent complexity of the rock mass makes it more difficult to control blasting effects, resulting in overbreak and underbreak as common issues in drill-and-blast tunnel construction.

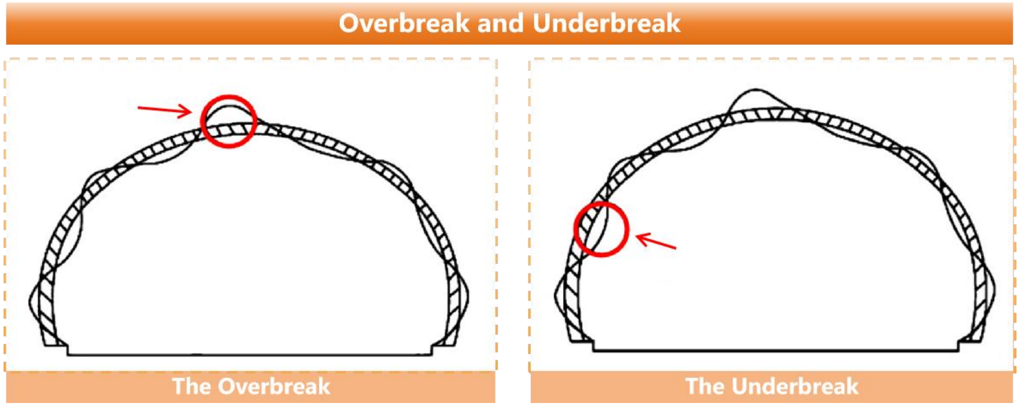

Figure 1. Schematic diagram of the overbreak and underbreak

The consequences of overbreak and underbreak are complex and multifaceted. Overbreak increases the volume of broken rock, thereby increasing costs for rock removal and waste disposal. Underbreak, in contrast, typically requires manual rock correction, which delays subsequent blasting cycles and, in turn, prolongs the project timeline. Traditional analysis of overbreak and underbreak depends on the manual selection of multiple tunnel sections for individual measurements, a time-consuming process susceptible to human error, thereby further extending the construction period. Therefore, an efficient and accurate detection method for overbreak and underbreak is essential for enhancing the quality and efficiency of drill-and-blast tunnel construction.

To address this challenge, this study proposes a detection method for overbreak and underbreak based on Digital Twin technology. Digital Twin technology facilitates the creation of a digital representation of a physical entity, enabling computational analysis in a virtual environment. In this study, 3D laser scanning technology is utilized to acquire the actual 3D model of the tunnel, which is subsequently compared with the design model. By analyzing the contour differences between these two models, the volumes of overbreak and underbreak are computed. Compared to traditional manual measurement methods, this approach offers superior efficiency and accuracy, significantly improving quality management in tunnel construction and providing an effective solution for the intelligent management of tunnel construction quality.

2 Related Work

2.1 The Influence of Overbreak and Underbreak

In mountain tunnel construction, the drill-and-blast method is one of the most widely used excavation techniques, and the evaluation of construction quality is closely tied to the levels of overbreak and underbreak. These deviations directly affect construction progress and lead to increased support and maintenance costs. Specifically in drill-and-blast tunneling, due to the complexity of geological conditions and the uncontrollable nature of construction parameters, the cost of addressing underbreak is typically higher than that of overbreak. As a result, the principle of "better over than under" is often adhered to, making overbreak more common than underbreak in tunnel construction (Koopialipoor et al., 2019). Overbreak and underbreak primarily arise from geological conditions, deviations between design and actual conditions, and human influence during operations (Van Eldert, 2017; Verma, 2018). Overbreak and underbreak caused by geological conditions can be partially controlled by improving preliminary investigation methods and optimizing blast designs, while deviations arising from design or execution issues can be mitigated by adjusting blast parameters (Singh, S.P. & Xavier, P., 2005). Overbreak and underbreak have significant adverse effects on the overall stability of tunnels, potentially leading to rock instability, water leakage, and increased support costs. In recent years, an increasing body of research has focused on optimizing drill-and-blast parameters and evaluating the impact of overbreak and underbreak on tunnel construction. For instance, Lei Mingfeng et al. (2023) proposed an instance segmentation algorithm for muck block size based on deep learning, which has shown promising engineering applications in optimizing blast parameters for mountain tunnels. Additionally, Ding Xiang (2022), using the Jian Mountain Tunnel project on the Zhonglan Railway as a case study, employed discrete element numerical simulation to examine the effects of interlayer dip angles on blast-induced overbreak and underbreak, resulting in optimized blast design solutions.

2.2 Measurement Methods and Technological Advances in Overbreak and Underbreak

With the continuous development of tunnel overbreak and underbreak measurement technologies, two primary approaches are currently employed: the traditional total station method and digital model analysis (Kim, Y. & Bruland, A., 2019). Since the 1980s, total stations have been widely used in tunnel engineering; however, this method requires substantial manual measurement, making it time-consuming and prone to significant errors and inefficiencies, which negatively impact project costs. Consequently, total stations have been progressively replaced by more efficient three-dimensional (3D) model-based methods (Alhaddad, M., 2016; Huang, Y. et al., 2022). The 3D model analysis approach primarily includes close-range photogrammetry and 3D laser scanning technologies, both of which assess overbreak and underbreak by collecting 3D data and comparing it with the design drawings (Wei, Z., 2023). Close-range photogrammetry involves the use of professional optical cameras to capture images, and recent technological advances have facilitated faster data transmission and processing (Chaoyang Jin et al., 2021). Meanwhile, 3D laser scanning, an emerging technology, utilizes laser ranging to collect 3D coordinates (Haishan Zhu & Sheng Li, 2021). The data is then processed and compared with the design drawings to assess levels of overbreak and underbreak. Recent studies indicate that overbreak and underbreak detection technology based on 3D laser scanning can automatically identify the quantity, location, and volume of overbreak and underbreak (Xuan Xie et al., 2024) and offers significantly higher accuracy than traditional total station or close-range photogrammetry methods (Wei, Z., 2023). Additionally, some studies have proposed analytical methods based on fitting point cloud surfaces to design surface normals to accurately calculate tunnel overbreak and underbreak volumes (Fang et al., 2024).

2.3 Prediction and Optimization of Tunnel overbreak and underbreak

In addition to existing measurement technologies, the prediction and optimization of overbreak and underbreak using artificial intelligence and machine learning methods have become key research focuses in recent years. For instance, Biao He et al. (2023) developed a hybrid model based on random forests to predict overbreak volume, which has been validated in multiple engineering projects. Amin Hekmatnejad et al. (2024) proposed a “Universal Discontinuity Index” (UDI) to predict the geometric characteristics of tunnel overbreak and underbreak. Furthermore, G.M. Foderà et al. (2020), in their study of the Brenner Base Tunnel (BBT), developed an operational method to estimate overbreak volume, distinguishing between technical overbreak caused by deficiencies in drill-and-blast design and execution, and geological overbreak influenced by rock mass characteristics.

These predictive models and algorithms leverage big data and deep learning techniques to forecast tunnel overbreak and underbreak, providing robust support for the optimization of tunnel blast parameters. However, due to the unpredictability of geological conditions, subjective construction practices, and inconsistent adherence to construction specifications, overbreak and underbreak in tunnels remain difficult to fully mitigate. These factors pose significant challenges to the accurate prediction of overbreak and underbreak. Current machine learning and deep learning methods primarily base predictions on numerical data and distribution patterns of overbreak and underbreak, which fail to account for all influencing factors. Therefore, the rapid detection and localization of overbreak and underbreak after each blast cycle remain crucial for on-site construction management. Real-time data on tunnel overbreak and underbreak plays a vital role in designing appropriate corrective and repair strategies.

3 Methodology

The fusion analysis of the design model and point cloud model near the tunnel face facilitates the accurate calculation of overbreak and underbreak. This study employs the concept of Digital Twin to establish a mapping between physical space and digital space. The corresponding design model and reality-based model in the digital space are derived from the physical space, as shown in the Figure 2.

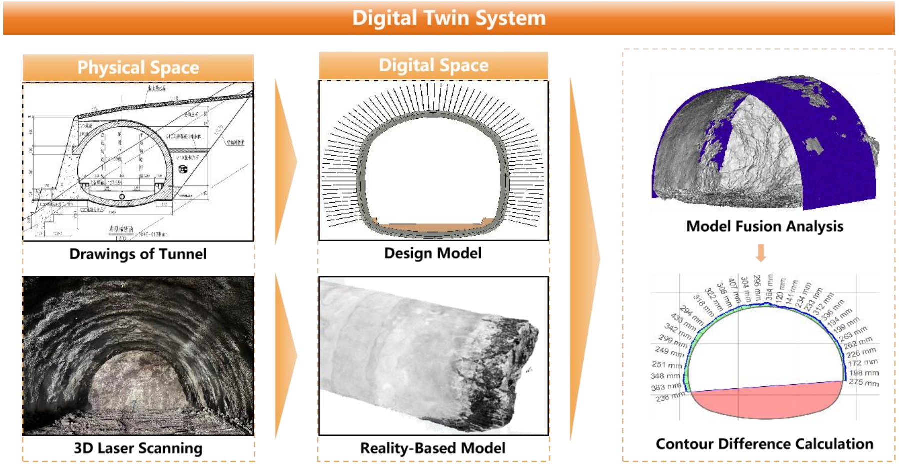

Figure 2. Construction of the Digital Twin System

3.1 Data Collection and Point Cloud Processing

This study primarily employs three-dimensional laser scanning technology. 3D laser scanning is a non-contact measurement technique based on laser ranging. It functions by emitting laser beams and receiving reflected signals, accurately measuring the spatial coordinates of the target object. Using high-density point cloud data, 3D laser scanning technology can generate detailed digital models of real-world objects and is widely applied in fields such as engineering surveying, building inspection, and tunnel engineering. The Faro Focus 350 employed in this study is a high-precision, stationary 3D laser scanner, specifically designed for rapid and efficient scanning of large and complex environments. This device has a scanning range of up to 300 meters and a measurement speed of 976,000 points per second, enabling the rapid generation of high-resolution point clouds. Additionally, it offers exceptional measurement accuracy, with errors as small as one millimeter, making it ideal for engineering scenarios requiring high precision, such as tunnels.

During data collection, the first step involves selecting appropriate scanning locations on the tunnel construction site to ensure complete coverage of the tunnel's interior profile. Next, scanning parameters such as resolution, scanning angle, and range are adjusted to meet the precision requirements. For overbreak and underbreak detection in tunnels, higher resolution is typically selected to capture detailed tunnel profile information. After scanning, the point clouds are aligned and stitched together between scan stations, followed by refined processing, such as denoising, filtering, and downsampling, to generate a reality-based model of the tunnel. By integrating the design model with the reality-based model, digital twin technology maps the physical and digital spaces, enabling accurate calculations of overbreak and underbreak volumes. This series of steps and technological applications ensures that overbreak and underbreak detection in drill-and-blast tunnel construction is precise and efficient, providing strong support for quality control in tunnel engineering.

3.2 Establishment of Reality-Based Model By Using 3D Laser Scanning Technology

The establishment of a reality-based model using 3D laser scanning technology is a critical step in the entire process. Its core lies in the collection, processing, and reconstruction of high-precision point clouds to achieve detailed modeling and analysis of tunnel structures. This process involves several steps, including preliminary processing and refinement of point cloud data, 3D reconstruction, and the final generation of the reality-based model.

Once point cloud data are collected, the first step is to process the raw data. Due to the complexity of the field measurement environment, point cloud data may contain significant noise, redundant data, and local anomalies. The primary task of point cloud processing is to enhance data clarity, reduce noise interference, and optimize the overall quality of the point cloud data.

Denoising is the first step in point cloud data processing. In this study, the Radius Outlier Removal (ROR) method is employed. By setting a fixed radius, any point with fewer neighboring points within this radius than a preset threshold is considered a noise point. This method effectively removes outliers, ensuring the continuity and accuracy of the point cloud.

To optimize point cloud resolution and reduce redundant data, the Octree method is employed for downsampling. This method divides the Cartesian coordinate system into eight quadrants, layering the original point cloud. Representative points are selected from each layer to replace multiple points within that region, thus reducing the data volume while preserving the geometric features of the point cloud. This processing efficiently encodes nodes and enhances the processing efficiency and decoding speed of the point cloud data.

After point cloud processing, the next step is 3D reconstruction using the point cloud. A commonly used method in 3D reconstruction is triangulation, where the point cloud is transformed into a polygonal mesh model that represents the surface geometry of the target. Poisson surface reconstruction uses normal vector information from the point cloud to solve Poisson equations and generate a continuous, smooth surface, which is particularly useful for point cloud data with noise or local gaps.

Once the initial mesh is generated through triangulation, surface fitting and mesh optimization are performed to improve the smoothness and accuracy of the model. Surface fitting can be achieved using mathematical methods such as NURBS (Non-Uniform Rational B-Splines) or B-spline surfaces, which smooth complex surfaces and eliminate sharp surface irregularities. Mesh optimization adjusts the vertices and edges of the mesh to ensure the generated model maintains geometric accuracy while achieving higher mesh quality.

Through point cloud processing and 3D reconstruction, the reality-based tunnel model is generated (Fig. 3). This model is not only a digital replica of the physical world but also serves as the foundation for further analysis. In overbreak and underbreak detection, comparing the geometric profiles of the reality-based and design models is a key step. By overlaying the reality-based model with the design model, accurate calculations of overbreak and underbreak volumes in the surrounding rock can be made. This 3D laser scanning-based analysis method significantly enhances detection precision and efficiency, providing reliable technical support for tunnel construction quality control.

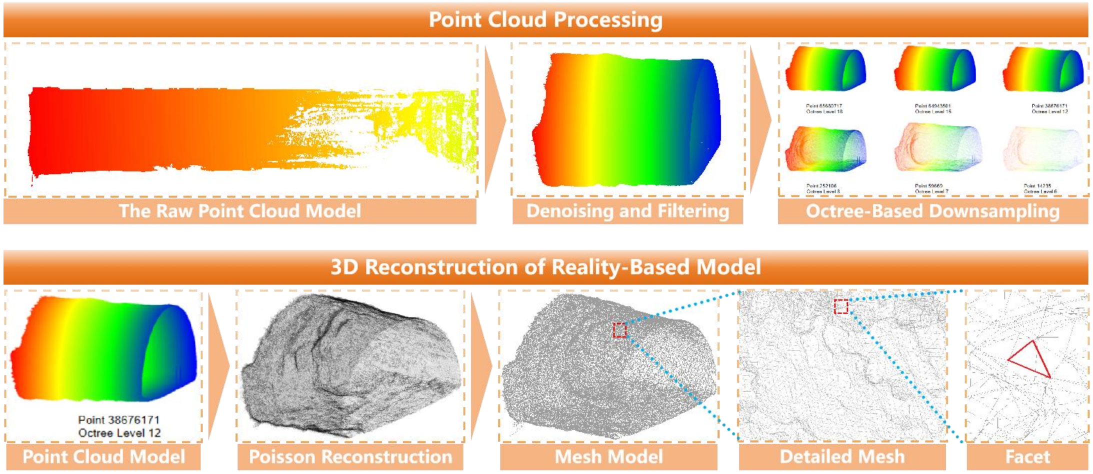

Figure 3. Tunnel Reality-Based Model Construction Process

3.3 Calculation Method for Overbreak and Underbreak

Since the design model is based on drawings, its coordinate system typically follows a standard geodetic coordinate system, while the reality-based model, generated through 3D laser scanning technology, uses an internal coordinate system. To achieve accurate overbreak and underbreak calculations in the tunnel, it is essential to align these two models within the same coordinate system. This ensures geometric consistency and relative accuracy between the models. Therefore, a coordinate system datum transformation is a crucial step before performing overbreak and underbreak calculations.

The Bursa seven-parameter coordinate transformation model can be used to align the two coordinate systems. This model, based on affine transformation, uses seven parameters - translation along three axes, rotation, and a scale factor - to achieve precise conversion from the internal to the geodetic coordinate system. The core of the Bursa model involves calculating transformation parameters using known control points that can be accurately identified in both coordinate systems. In this study, key points are extracted from the point cloud model by identifying critical nodes such as the tunnel crown, invert, and sidewalls. The known coordinate points are then obtained and matched to the design drawings. Using optimization methods such as the least squares method, the parameters are calculated, and the coordinate transformation subsequently maps the reality-based model to the geodetic coordinate system.

Once the datum transformation is complete, both the design and reality-based models will share the same coordinate system, ensuring geometric consistency in space. This forms the foundation for subsequent overbreak and underbreak calculations. Using this coordinate transformation method, the reality-based tunnel model is accurately aligned with the design model, enabling precise identification of overbreak and underbreak regions. This enables the construction and detailed analysis of the digital twin model.

3.3.1 Calculation of Overbreak and Underbreak Distances

The calculation of overbreak and underbreak volumes is fundamentally based on the geometric comparison between the reality-based and design models. Both models are represented as 3D mesh structures composed of multiple triangular facets, where each facet is defined by three vertices, and each with unique spatial coordinates. Consequently, the calculation process involves determining the distance from the vertices of the reality-based model's triangular facets to the corresponding facets of the design model, as shown in Figure 4. The following outlines the procedure for calculating overbreak and underbreak distances:

(1) **Extraction and Sorting of Triangle Facets in the Design Model:** The triangular facets in the design model are extracted and sorted into a sequence within a triangular facet group. One triangle facet is selected from this group at a time for subsequent calculations.

(2) **Check the Vertex Projection:** For each selected triangular facet A in the design model, corresponding vertices Pi (xi, yi, zi) in the reality-bases model are sequentially searched. For a vertex in the reality-based model, it is necessary to determine whether the vertex can project onto the triangular facet A of the design model. If the projection of the vertex falls inside the triangular facet A, the vertex is recorded in the array [P1, P2, P3, ... , Pn].

(3) **Point-to-Facet Distance Calculation:** If the projection of the vertex Pi falls inside the triangular facet A of the design model, the distance from the vertex Pi to the triangular facet A is calculated. The distance D between a point P(xp, yp, zp) and a triangle plane can be calculated using the point-to-plane distance formula. The resulting distance Di is stored in the corresponding distance array for that triangular facet A.

(4) **Retrieving Other Vertices and Updating Distance Groups:** The next vertex in the reality-based model is retrieved, and the projection check and distance calculation process is repeated. If the vertex can be projected onto the triangular facet of the design model, its distance to the facet is calculated and stored in the corresponding distance array for that triangular facet, until all vertices have been checked. If there are n valid vertices within the facet A, its corresponding distance group is created as [D1, D2, D3, ... , Dn].

(5) **Calculation of Overbreak and Underbreak for Each Triangle Facet:** For each triangular facet in the design model, the final overbreak and underbreak distance is determined by the minimum value in its corresponding distance array, denote as Dmin=min(D1, D2, D3, ... , Dn). The Dmin represents the overbreak or underbreak for the triangular facet, the symbols "+" and "-" represent overbreak and underbreak, respectively, reflecting the geometric deviation between the reality-based model and the design model in the corresponding region.

(6) **Global Overbreak and Underbreak Distance Calculation:** The above process is repeated for all triangular facets in the design model, sequentially retrieving and calculating distances, until the overbreak and underbreak volumes for all facets are determined. Then each triangular facet in the design model corresponds to an overbreak or underbreak distance. By aggregating the overbreak and underbreak distances from all facets, a comprehensive overbreak and underbreak analysis for the entire tunnel can be conducted.

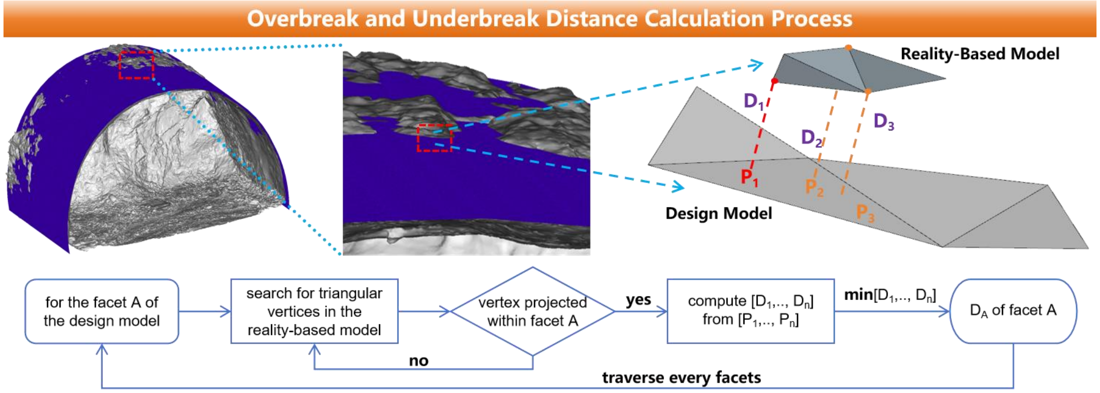

Figure 4. Overbreak and Underbreak Distance Calculation

3.3.2 Area and Volum Calculation of Overbreak and Underbreak

In drill-and-blast tunnel engineering, the overbreak area serves as a critical indicator for assessing the geometric deviation of tunnel cross-sections. The calculation of the overbreak area for a specific cross-section involves introducing a sliding plane, perpendicular to the longitudinal axis of the tunnel, which intersects both the reality-based model and the design model, as shown in Figure 5. The overbreak area for a given cross-section is computed through the following steps:

(1) **Introduction of the Sliding Plane:** The sliding plane is defined as the chosen tunnel cross-section. The position of the reference plane is established according to the longitudinal coordinates of the tunnel.

(2) **When the sliding plane intersects the vertices:** If the sliding plane intersects the vertices of the triangular facets in the reality-based model, the overbreak distance can be calculated based on the results presented in section 3.3.1.

(3) **When the sliding plane intersects the facet:** If one or two vertices of the triangular facet lie on opposite sides of the sliding plane, the sliding plane intersects the facet. Given the equation of the sliding plane and its perpendicular orientation to the longitudinal axis, the intersection points between the plane and the triangular facet occur at the same longitudinal position. Using the line equation and the coordinates of the intersection points, the coordinates of intersections A(xa, ya, za) and B(xb, yb,zb) between the sliding plane and the two edges of the triangular facet can be computed.

(4) **Elimination of Redundant Intersection Points:** Since triangular facets in the real-world model are adjacent, one edge of an intersected triangular facet may be counted twice. Sorting the intersection points based on their polar coordinate angles removes redundant points, resulting in a unique array of intersection points between the reference plane and the real-world model.

(5) **Selection of Triangular Facets from the Design Model:** After obtaining the array of intersection points for the real-world model, the triangular facets from the design model that intersect with the reference plane are identified. This results in a set of triangular facets from the design model.

(6) **Distance and Area Calculation:** The distances L between adjacent intersection points in the array are measured. Using the results from section 3.3.1, the distances D between the intersection points and the triangular facets of the design model are computed. By integrating these distances, the overbreak and underbreak area for the sliding plane's cross-section is computed.

(7) **Calculation of Overbreak and Underbreak Volume Along Steps:** By shifting the sliding plane along the longitudinal axis of the tunnel, the overbreak and underbreak areas for each cross-section are determined. The total overbreak and underbreak volume for the tunnel blast section is obtained by integrating the overbreak areas as the sliding plane moves, thereby completing the entire calculation process.

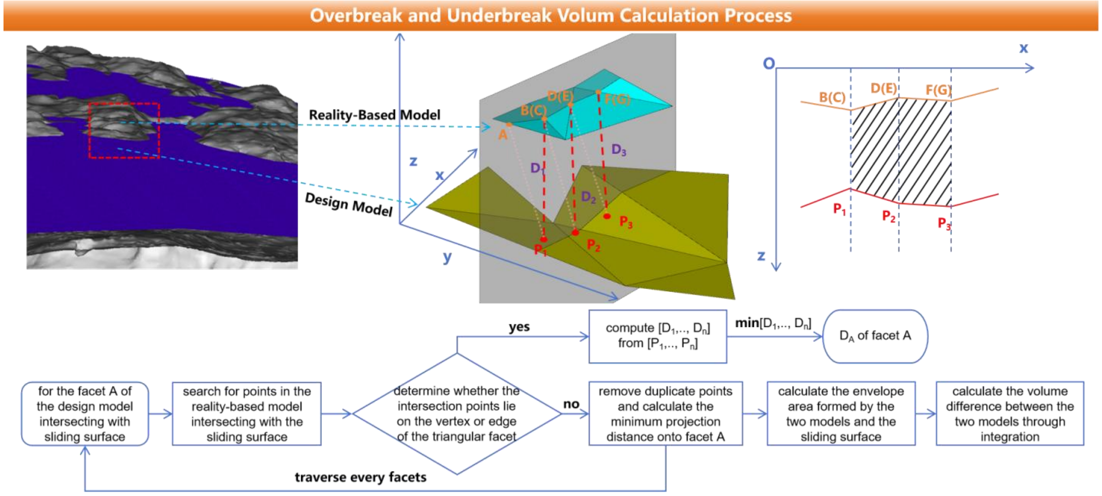

Figure 5. Overbreak and Underbreak Volum Calculation

Through the aforementioned calculation process, the overbreak distance is first calculated based on the geometric relationship between the reality-based model and the design model. Next, the overbreak area for each cross-section is determined using the polygonal method, and the total overbreak volume for the tunnel is obtained through numerical integration. This series of methods ensures the accuracy and operability of model comparison and analysis, effectively quantifying the volume of the overbreak area and providing a theoretical basis for refined management and construction optimization in tunnel engineering.

4 Result

To enhance the visualization of the calculation results, this study divides the tunnel cross-sections by angle and assigns a unique identifier to each cross-section. By calculating the overbreak and underbreak areas at each position along the cross-section, the overbreak and underbreak for the entire cross-section can be visualized, facilitating statistical analysis of the areas and their distribution patterns. Furthermore, by introducing sliding step lengths (d1, d2, d3), the overbreak and underbreak areas for multiple cross-sections within each step length can be computed, and these areas are then integrated to calculate the total volume, as shown in Figure 6. Theoretically, the finer the division of the tunnel cross-sections, i.e., the greater the number of identifiers assigned to each cross-section, the more precise the calculated overbreak and underbreak areas. Similarly, for a given tunnel segment, the smaller the step length (d), the more accurate the calculated overbreak and underbreak volume. This method allows for flexible adjustment based on the requirements for calculation time and accuracy, thereby optimizing the process of overbreak and underbreak detection. It provides greater flexibility and robustness in actual construction project management, offering an efficient and precise method for evaluating tunnel blasting quality.

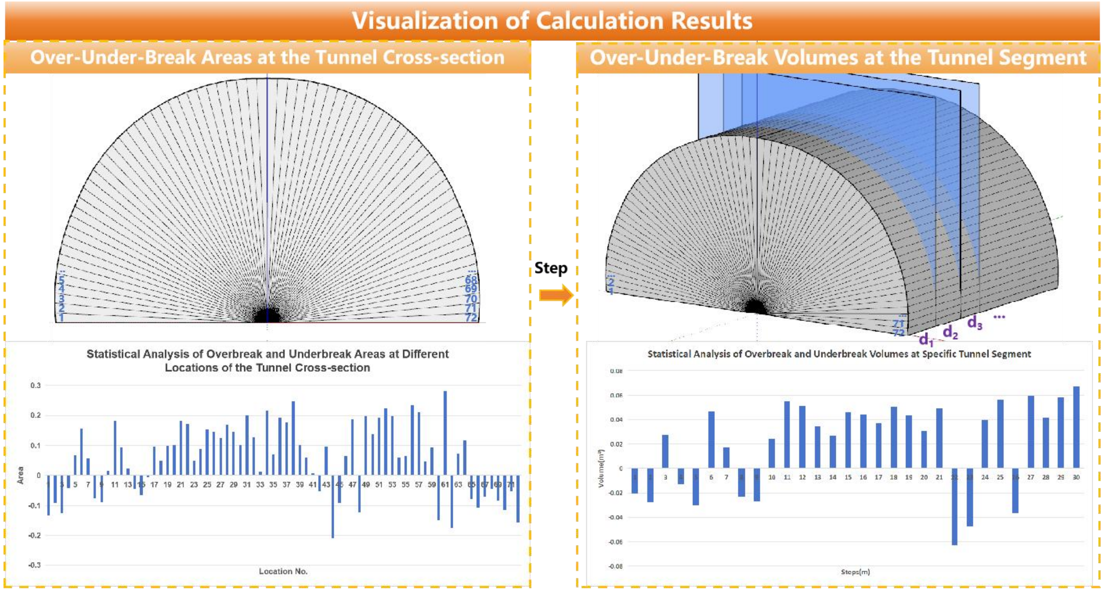

Figure 6. Calculation and Statistics of Tunnel Overbreak and Underbreak Area and Volume

5 Conclusions

This study proposes an efficient method for detecting tunnel overbreak and underbreak by applying 3D laser scanning technology, point cloud processing, and triangulation techniques to establish a three-dimensional reality-based model of the tunnel, while also constructing the design model based on blueprints. Utilizing digital twin theory, issues traditionally addressed through manual measurements in the physical space are mapped into the digital space, where tunnel overbreak and underbreak detection is achieved through digital model processing and analysis. The detection results are visualized to guide tunnel blasting quality control in the physical space. Compared to traditional measurement methods that require significant human resources, the 3D reconstruction and integrated model analysis, driven by digital twin technology, reduce the reliance on labor-intensive management practices for tunnel construction by replacing manual labor with efficient computational methods. This approach also mitigates subjective errors associated with different personnel, thereby enhancing measurement accuracy. The digital overbreak and underbreak detection method provided in this study supports efficient and precise quality control of drill-and-blast tunnel construction and lays a foundation for achieving intelligent tunnel construction management.

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