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Research Article

Addressing Tunnel Segment Misalignment Challenges: A Comparative Analysis of Detection Techniques

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ABSTRACT

Tunnel misalignments compromise safety and efficiency in transportation and utilities. Visual inspection is imprecise, such as laser scanning and digital image correlation are required that lacks efficacy and stakeholder perception study like stakeholder perceptions. Check out these techniques towards stakeholder perspectives for project-specific features and user experiences, research can help improve tunnel engineering project decision-making, detection accuracy, and operational efficiency, hence ensuring tunnel infrastructure network reliability and safety. Tunnel segment misalignment detection, a major tunnel engineering difficulty, is researched to improve accuracy and efficiency. The main goals are detection method evaluation, stakeholder perspectives, and tunnel engineering insights. Mixed methods are employed for quantitative testing with different misalignment levels and qualitative tunnel builder interviews. Quantitative analysis examines visual inspection, laser scanning, total station, ultrasonic testing (UT), and digital image correlation (DIC). Low experimental % errors help laser scanning and DIC discover misalignments. UT is large, but total station and eye exam can detect smaller misalignments. The longest procedure studied is DIC. Qualitative stakeholder interviews enhance findings. Laser scanning is promising due to its accuracy and simplicity, yet cost and complexity persist. Visual inspection is simple yet subjective and error-prone. Qualitative insights help tunnel engineering project decision-making by revealing stakeholders' preferences and concerns as per stakeholder perspectives. The research has many effects that help to choose misalignment detection methods based on accuracy, usability, and cost. Qualitative stakeholder interviews inform training and equipment procurement for detection. This study exhibits misalignment detecting devices' performance and tunnel engineering benefits, offering practical applications for improving tunnel infrastructure detection accuracy, efficiency, safety, reliability, and user-friendly field technologies through qualitative analysis.

Keywords: Tunnel Infrastructure, Misalignments, Detection Techniques, Safety, Operational Efficiency.

INTRODUCTION

Tunnel segment misalignment, a key civil engineering and infrastructure development issue, can impair structural integrity, operational efficiency, and safety. Understanding tunnel segment misalignment's origins, from construction errors to geological irregularities, emphasizes the importance of precise alignment while digging (Chai et al., 2023). Segment misalignment increases structural instability, load-bearing capacity, frictional resistance, derailment, and structural failure dangers, requiring stringent mitigation procedures. Tunnel segment misalignment identification, assessment, and correction require careful consideration and interdisciplinary collaboration, combining structural engineering, geotechnical analysis, and material science to create robust solutions that reduce misalignment-induced problems and improve subterranean infrastructure network longevity, reliability, and safety (Ahmad et al., 2021; Ali et al., 2020; Nawaz, Su, & Nasir, 2021; Ji, Su, Qin, & Nawaz, 2021). Quality control, advanced monitoring technologies, and adaptive design frameworks strengthen tunnel structures against dynamic environmental conditions and operational exigencies and improve tunneling efforts to foster sea life (Xiao et al., 2019).

Tunnel segment misalignment in civil engineering and infrastructure development is complicated by subterranean route construction and operation. In an increasingly interconnected world, innovation and progress require better transit, connection, and urban resilience (Liu, Chen, Zhang, & Wang, 2021). Tunnel segment misalignment is difficult due to geological diversity, technological complexity, and operating needs. Tunnel building requires precision and accuracy. Tunnel alignment is problematic due to geology, construction methods, and materials. The geological substrate's variety and unpredictability provide unstable ground conditions, geological discontinuities, segment alignment variations, and structural integrity issues. Tunnel boring, cut-and-cover, and immersed tube processes can misalign due to equipment, construction, and human errors (Singh, Mittal, Gupta, & Khan, 2023).

Misalignment worsens tunnel infrastructure operations, from car traffic to rail transportation, emphasizing the importance of perfect alignment for efficiency, safety, and resilience. Misalignment impacts structural stability, load-bearing capacity, and operating safety, necessitating holistic diagnosis, assessment, and mitigation (Valiante, Elgarhi, Lazzarin, Crapp, & Stucchi, 2023). To tackle tunnel segment misalignment's complex issues and reduce risk, structural engineering, geotechnical analysis, and materials research are needed. Through rigorous quality control, innovative monitoring technologies, and adaptive design frameworks, stakeholders can improve tunnel structures' resilience to dynamic environmental conditions and operational demands to ensure sustainable, resilient, and safe subterranean infrastructure networks (Braga, Zapico, Tyagi, & Bono, 2023).

Tunnel engineering and infrastructure building require precise detection technologies to reduce tunnel section misalignment (Ma et al., 2024). Face detection and recognition technologies have been prevalent for several decades (Al-khafaji, 2024). Underground tunnel integrity, functioning, and safety engineers use modern detection systems. From traditional surveys to advanced monitoring systems, detection methods reveal tunnel segment alignment, deformation, and structural integrity. Tunnel construction is hard; therefore detection approaches provide real-time data, actionable insights, and forecasting skills to help stakeholders identify, assess, and resolve misalignment issues. Each detecting method has pros, downsides, and tunnel engineering uses. Traditional trigonometry and geodesy surveying measures angles, distances, and coordinates with total stations, theodolites, and GPS. Engineers can effectively map and monitor three-dimensional surfaces, deformation patterns, and structural anomalies using LiDAR and photogrammetry (Hu, Sun, B. Wu, H. Wu, & Xu, 2024; Keil, 2019; S. Zhao, Shadabfar, Zhang, Chen, & Huang, 2021).

Non-invasive, quick, and extensive tunnel alignment, geotechnical, and environmental dynamics studies are possible with satellite photos, GPR, and UAVs. Sensor networks, distributed fiber-optic sensing, and IoT platforms allow stakeholders to predict difficulties and optimize maintenance protocols by monitoring structural behavior, stress distributions, and deformation trends in real time (Hu, Zhang, Wu, Li, & Zhou, 2022; Huang, Cheng, Zhou, Chen, & Zhao, 2020). When picking detection methods, stakeholders must consider technological feasibility, cost-effectiveness, scalability, and regulatory compliance. Geotechnical engineering, data science, and risk management must balance detection technique selection and deployment for each tunneling project (S. Zhao et al., 2021). Through innovation, collaboration, and continual improvement, stakeholders can apply detection approaches to improve tunnel engineering resilience, safety, and sustainability, enabling seamless connectivity, optimized performance, and increased societal well-being.

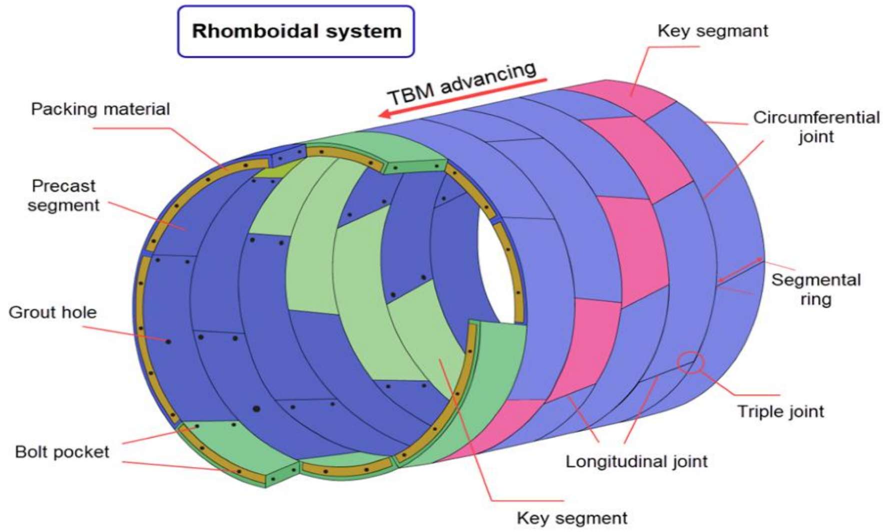

Figure 1. An Obliquely Joined Segmental Tunnel Lining in Three Dimensions

Figure 1 shows an obliquely connected segmental tunnel liner over three dimensions. The illustration depicts the tunnel lining's complex structure and how the sections form the cylindrical tube. From an odd angle, viewers can observe the tunnel's shape and alignment. The tunnel lining segments are clearly outlined, showing the accuracy needed in manufacturing and installation for alignment and structural integrity. To demonstrate tunnel lining construction and composition, the graphic may depict reinforcement elements or surface textures. **Figure 1** aids tunnel engineers, academics, and stakeholders in project visualisation. It helps with tunnel lining design, arrangement, alignment, stability, and performance (Xue, Shi, Jia, & Huang, 2022).

Tunnel sections are misaligned by civil engineering and infrastructural innovation. Tunnels facilitate communication and transportation in heavily lived areas. Due to geological uncertainty and technical complexity, subterranean line construction and maintenance may misalign tunnel segments. Since ground characteristics and formations affect segment alignment and stability, geological diversity hinders tunnel construction. Geological substrates including soil instability, rock fracture, and faults can affect tunnel segment alignment and structural integrity. Complex geology and construction exacerbate tunnel misalignment. Tunnel boring, cut-and-cover, and immersed tube alignment require coordinated materials, personnel, and equipment (Hu et al., 2022; Tian, Li, He, & Zhang, 2023; S. Zhao et al., 2021). Segment alignment discrepancies from equipment, structural, and human errors can increase misalignment.

Alignment is made worse by tunneling. Environmental influences and dynamic stress can cause misalignment in utility, rail, and automotive tunnels. The direction of tunnel infrastructure affects maintenance, safety, and operating effectiveness. Tunnel segment misalignment detection and correction are highlighted here. Stakeholders can identify and correct misalignments with the use of Visual Inspection, Laser Scanner, Total Station, Ultrasonic Testing (UT), and Digital Image Correlation (DIC). Comparing and understanding these options will require more research in order to improve tunnel engineering resilience, safety, and sustainability (Helmers et al., 2020; Hu et al., 2024; Qiu, Liang, Wang, Tong, & Wan, 2022).

Visual Inspection, Laser Scanner, Total Station, Ultrasonic Testing (UT), and Digital Image Correlation (DIC) are utilized to correct tunnel segment misalignment, but their knowledge and comparison analysis are limited. Many tunnel segment misalignment detection methods have been studied, but few have been tested in tunnelling. The comprehensive factors affecting these technologies' application, performance, and limitations are often disregarded. Comparisons of detection systems are difficult without evaluation standards and benchmarking frameworks, impeding strategy optimisation and decision-making. Visual Inspection, Laser Scanner, Total Station, Ultrasonic Testing (UT), and Digital Image Correlation (DIC) must be evaluated for tunnel segment misalignment detection and mitigation efficacy, accuracy, cost-effectiveness, and scalability. This study uses Visual Inspection, Laser Scanner, Total Station, Ultrasonic Testing (UT), and Digital Image Correlation to identify tunnel segment misalignment. Rigours analysis assesses tunnelling methods' efficacy, accuracy, cost, and scalability. Tunnel engineering stakeholders may weigh detecting system merits and downsides (Huang et al., 2020; Qiu et al., 2022; Tian et al., 2023).

Although detection methods lessen misalignment hazards, knowledge gaps and evaluation and comparison concerns remain. Tunnel engineering plan optimisation and decision-making are difficult without standard evaluation criteria and benchmarking frameworks (Huang et al., 2020; Qiu et al., 2022; Tian, 2023). Not understanding how each detecting technology works, its pros, cons, and applications limits stakeholder selection. To remedy these information gaps, this study evaluates detection approaches, benchmarks their effectiveness, and suggests best practices to increase tunnel infrastructure alignment accuracy, efficiency, and safety. This study tackles information gaps and advises tunnel engineering and underground infrastructure network resilience, safety, and sustainability.

This research affects tunnel alignment safety, efficiency, and accuracy. This study helps stakeholders evaluate detection system performance, accuracy, and cost to improve tunnel engineering. This study identifies detection method best practices to improve tunnel infrastructure alignment accuracy, efficiency, and safety. By systematically comparing detection methods, benchmarking systems and evaluation criteria encourage industry best practices. Standardising evaluation criteria ensures tunnel engineering detection technique selection and deployment across projects. To change tunnel engineering, this research bridges knowledge gaps and improves tunnel engineering methods to increase underground infrastructure network resilience, safety, and sustainability. This research's detailed analysis and recommendations assist tunnel engineering for society's changing needs. This study recommends tunnel segment misalignment detection system changes to improve tunnel infrastructure efficiency, safety, and sustainability.

LITERATURE REVIEW

Tunnel segment misalignment's implications on civil engineering and infrastructure development are well-studied. Through historical case studies, geological surveys, and engineering simulations, scholars have identified geological abnormalities, construction defects, operational needs, and dynamic environmental variables as tunnel segment misalignment reasons. Tunnel building requires precision since even little alignment errors can compromise underground infrastructure network structural integrity, efficiency, and safety. Experimental research illustrates the detection and mitigation's pros and cons (Chen, Zhang, Liao, & Peng, 2016; Daoust, Pomerleau, & Barfoot, 2016; Hu et al., 2024).

Total tunnel section misalignment literature analysis shows civil engineering and infrastructure diversity. Scholars say geological complexity, construction methods, operational needs, and changing environmental conditions jeopardize tunnel alignment. Empirical studies show tunnel segment misalignment affects operational efficiency, safety, and maintenance beyond structural issues. Numerous case studies show that misalignment increases frictional resistance, load-bearing capacity, derailment, and structural failure. The literature included tunnel section misalignment detection and mitigation. Misalignment detection and repair were examined using visual inspection, laser scanning, total station surveys, ultrasonic testing (UT), and digital image correlation (DIC) (Aldibaja, Suganuma, Yoneda, & Yanase, 2022; Tian et al., 2023).

Standardised evaluation criteria and benchmarking systems enable rigour detection method comparisons and industry best practices. The literature study recommends precision engineering, current monitoring technology, and interdisciplinary collaboration to ensure subsurface infrastructure network res Tunnel engineering's methodologies are highlighted in the literature study on tunnel segment misalignment detection. Researchers have thoroughly examined several misalignment detecting systems, each with merits and cons. Trigonometry and geodesy have long been used to determine alignment accuracy. Total station surveys let engineers assess alignment by measuring angles, distances, and coordinates. Besides these methods, visual inspection can reveal surface problems and misalignment. Recent technological advances have made detection procedures more efficient and accurate. Engineers can map surface topography and deformation patterns in 3D using laser scanning. Photogrammetry creates high-resolution tunnel infrastructure models for alignment deviation investigation from aerial photographs (Helmers et al., 2020; Hu et al., 2022; S. Zhao et al., 2021).

Tunnel alignment testing can also be done non-invasively with GPR and UAVs. GPR systems identify subsurface soil and rock anomalies, while UAVs map and monitor tunnel infrastructure. Ultrasonic testing (UT) and DIC show structural behaviour and deformation patterns in real time. UT systems use high-frequency sound waves to find tunnel segment faults, while DIC methods use digital images to measure displacement and deformation under varied loading conditions. The literature study highlights using several detecting methods to fix tunnel segment misalignment. Engineers can increase tunnel infrastructure network resilience, safety, and sustainability by using classic surveying methods and cutting-edge technologies to discover, assess, and fix misalignment issues. Resilience, safety, and sustainability (Daoust et al., 2016; Huang et al., 2020; Ma et al., 2024).

The literature analysis on tunnel segment misalignment variables illustrates how numerous factors affect tunnel engineering alignment precision and structural integrity. Researchers identified major variables affecting misalignment discovery and mitigation using empirical and theoretical frameworks. Studies reveal that soil type, rock formations, and geology affect tunnel segment alignment. Geological surveys have linked faults and discontinuities to misalignment, emphasising the need for thorough geological assessments in tunnel construction. Construction methods affect tunnel alignment (Hu et al., 2024; Keil, 2019; Wang et al., 2021). The study found that equipment failure, construction faults, and human error can misalign tunnel boring and cut-and-cover processes (Qiu et al., 2022).

Different building methods were tested for alignment accuracy and misalignment. Dynamic loads, environmental stressors, and vehicle traffic misaligned tunnel infrastructure networks. An empirical study linked traffic volume and vehicle speeds to misalignments, revealing detection and mitigating difficulties. Tunnel segment misalignment detection and mitigation for structural integrity and safety are emphasised in the literature (Braga et al., 2023; Chen et al., 2016; Xue et al., 2022). Laser scanning, optical inspection, total station surveys, ultrasonic testing (UT), and digital image correlation have been examined for detection. Researchers recommend multiple detection approaches to improve tunnel infrastructure network alignment assessment and accuracy. Geological difficulties, construction methods, operating needs, and tunnel section misalignment detection are discussed in the literature (Ashcroft, Børresen, Mamia, & Labe, 2023; Valiante et al., 2023; Zhang, Zhu, & Wei, 2022).

Technological innovations in tunnel misalignment detection have been researched. Automatic identification of point cloud misalignments is possible with LiDAR and deep learning. Tunnel section cracks were classified using machine vision to show structural flaws and misalignments. Misalignment detection and analysis can be improved by combining TLS with image processing or BIM. The findings show that automated defect detection systems, sensor-equipped UAV inspections, and real-time monitoring systems could discover misalignments and other flaws faster and safer in tunnel maintenance. Technology improves tunnel maintenance, enhancing subterranean infrastructure network resilience, safety, and sustainability.

A literature analysis suggests civil engineering and infrastructure development must address tunnel section misalignment. Minor alignment errors can impair structures, efficiency, and safety (Chai et al., 2023). Geological abnormalities, building faults, operational needs, and dynamic environmental variables cause tunnel misalignment, according to engineering models, geological surveys, and historical case studies. Comprehensive study reviews improve literature reviews. Tunnel structural quality and misalignment are often highlighted. Visual inspection, laser scanning, and other misalignment detection methods have been thoroughly explored, but fresh insights and synthesis are needed. Explain tunnel misalignment detecting technology (Chen et al., 2016; Daoust et al., 2016). Uncertainty about difficulty and detection methods slows the exam. The study framework must be justified to be comprehended. The assessment does not suggest research needs or answers. Find and close these gaps to advance the field. Study standards and detection method evaluation need more discussion. This clarifies the detection method comparison.

Tunnel segment misalignment has major effects on civil engineering and infrastructure development, as evidenced by considerable research. Geological irregularities, structural faults, and operating needs have been extensively studied as misalignment causes. Historical case studies, geological surveys, and engineering simulations reveal that geological complexity, building methods, and environmental circumstances threaten tunnel alignment. Misalignment significantly affects tunnel infrastructure network efficiency, safety, and maintenance, according to empirical investigations. Misalignments cause mechanical damage, friction, load-bearing capacity difficulties, and derailments. Advanced monitoring and precision engineering are essential for safe, sustainable tunnel infrastructure networks. A literature review can identify and mitigate misalignments, but it has limits. It evaluates prior studies and may not cover new technology or methodologies. Differences in study techniques and data interpretation may affect generalising conclusions from publications.

Further research should address these concerns and improve tunnel segment misalignment understanding. Improved detection and mitigation require technical innovation and interdisciplinary collaboration. Novel tunnel maintenance technology may be viable and beneficial after long-term research. Based on the literature, we got a research model based on the variables (**Figure 2**). **Figure 2** is a context-dependent research model, explaining the study's primary factors and linkages.

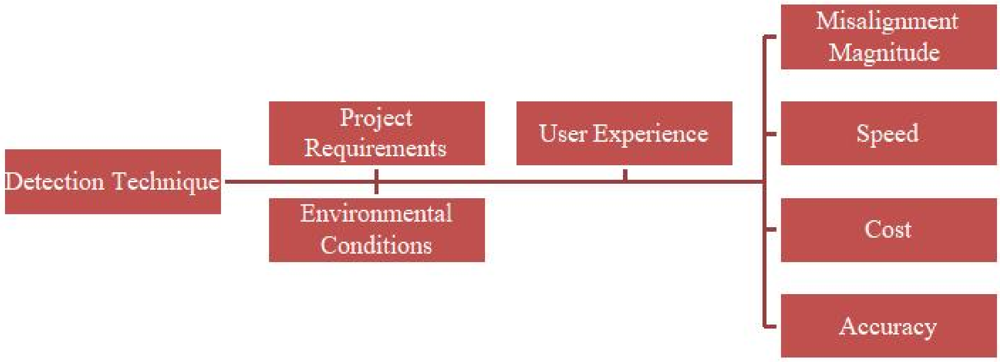

Figure 2. Research Framework

METHODOLOGY

The study evaluates tunnel segment misalignment utilizing quantitative and qualitative data and analytical frameworks. This extensive study examines tunnel engineering alignment accuracy elements' complicated interaction. Tunnel alignment surveys commence on-site. Surveys directly observe alignment deviations and structural anomalies, forming the basis for data collection. Tunnel geometry, deformation patterns, and structural behaviour are examined via laser scanning, DIC, and field surveys. High-resolution 3D tunnel infrastructure models using laser scanning and DIC enable alignment deviation analysis under varying loads. These approaches reveal misalignments' location and tunnel integrity effects. Computer simulations predict and assess misalignment-related structural deterioration. Modelling tunnel segments, geological substrates, and operating conditions replicate reality. Tunnel misalignment mechanisms are studied using numerical models, field surveys, and modern technology. A complete tunnel section misalignment investigation utilizes field surveys, current technologies, and numerical models. Researchers find patterns, trends, and alignment accuracy variables with this detailed procedure. Misalignment can be avoided via predictive models and mitigation. Quantitative and qualitative methods enable tunnel segment misalignment analysis. This method studies tunnel engineering and misalignment mechanisms using field data, contemporary technologies, and numerical models. This holistic analysis helps researchers make decisions, improve alignment, and maintain tunnel infrastructure network safety and reliability.

Data analytics and statistical modelling analyse massive field surveys, monitoring, and numerical simulation data. Researchers employ regression modelling and statistical investigations to uncover correlations between geological features, construction methods, operating demands, and misalignments. Tunnel segment misalignment detection systems are compared for efficacy, accuracy, and cost. Researchers can compare visual examination, laser scanning, total station surveys, ultrasonic testing (UT), and digital image correlation (DIC) to determine the optimal detection method. Field surveys, advanced monitoring technologies, numerical simulations, data analytics, and comparison analyses can investigate tunnel segment misalignment issues, helping tunnel engineering project discovery and mitigation.

Due to the elements and study, the research fully evaluates detection methods. The investigation initially chooses tunnel engineering detection procedures. Select from visual inspection, total station surveys, laser scanning, UT, and digital image correlation. Each method's technique or technology detects tunnel segment misalignment. Controlled experiments and field measurements quantify each detecting method. Quantitative variables include misalignment magnitude, precision, detection speed, and cost. Misalignment volume depends on tunnel segment distance (millimetres) and angular variation (degrees). Accuracy is affected by misalignment % inaccuracy. Costs and detection time will be examined. Controlled lab experiments simulate misalignment. These studies create controlled misalignments between tunnel segments of set dimensions and then measure and detect them using each detection method. Field measurements on tunnel construction sites verify lab results and test detectors (X. Zhao et al., 2023).

Each detection approach collects qualitative data on user experiences, contextual factors, and project goals through surveys, interviews, and observational studies. The tunnel builders, engineers, and managers attend. To evaluate each detection technique's practicality and limitations, user experience, ambient conditions, and project need to be considered.

Comparing quantitative and qualitative data requires statistics and qualitative analysis. Quantitative and qualitative tests evaluate tunnel segment misalignment detection methods. We verify and interpret analysis results through peer review, expert consultation, and reference to current literature and industry standards. Tunnel engineering and practice benefit from the findings and help to choose and deploy detection methods. This study will provide a solid framework for tunnel engineering project segment misalignment identification and mitigation.

The study evaluates tunnel section misalignment, a key engineering challenge, using quantitative and qualitative methodologies. Laser scanning, digital picture correlation, and surveying fix tunnel engineering misalignments. Novelly, the work stresses tunnel alignment accuracy's intricate interdependence. Field investigations, monitoring, and numerical simulations show tunnel segment misalignment processes at the complex intersection of geological causes, building methods, operating needs, and misalignments. This study pioneers data analytics and statistical modelling for massive field surveys, monitoring, and numerical simulation data. Regression modelling and statistical analysis assist tunnel engineering project forecasts by identifying misalignment sources. Tunnel builders, engineers, and project managers survey, interview, and observe detection systems in pioneering qualitative research. Interactive misalignment detection system evaluations integrate user experiences, contextual elements, and project goals, making judgements more realistic. New and detailed methods improve tunnel segment misalignment identification and mitigation in the study. This project will revolutionise tunnel engineering by detecting and resolving misalignments to improve tunnel infrastructure network safety, reliability, and efficiency.

RESULTS

Table 1 outlines tunnel engineering detection strategies, although more knowledge is needed. The basics are covered, but greater detail on each technique's steps would help readers apply it. Visual inspection is a manual procedure performed by qualified specialists, but characterising the visual signals or measurement equipment used during evaluations could improve its description and real-world application. A more detailed explanation of laser scanning, total station, ultrasonic testing (UT), and digital image correlation will help readers. **Table 1** compares the pros and cons of each detection method, although tunnel engineering demands further analysis. The advantages highlight accuracy, speed, and non-destructiveness, with technique-specific advantages adding nuance. Laser scanning detects fine surface features, while UT finds tunnel cracks and voids. Checking each detection technique's realistic constraints may help the limits column. **Table 1** acknowledges limits including visual inspection's subjectivity and laser scanning, total station, UT, and DIC equipment prices, but discussing them helps readers understand implementation obstacles. Explaining how lighting or surface textures make visual evaluation subjective may help explain its limitations. **Table 1** details tunnel engineering detection methods and their pros and cons. This clarity and depth of information would let tunnel engineering stakeholders pick and implement detection technologies, improving efficiency, accuracy, and safety.

Table 1. Detection Technique Overview

Detection Technique	Description (Functioning Principle)	Advantages	Limitations
Visual Inspection	Manual inspection by trained personnel	Low cost, readily available	Subjective, prone to human error, limited accuracy
Laser Scanner	Uses laser beams to create a 3D point cloud of tunnel segments	High accuracy, fast data collection	Requires line of sight, expensive equipment
Total Station	An optical surveying instrument for measuring angles and distances	Accurate for long distances, versatile	Requires skilled operator, complex setup
Ultrasonic Testing (UT)	Uses high-frequency sound waves to detect misalignment	Non-destructive, highly accurate for small cracks/voids, good penetration depth	Requires smooth surface, complex result interpretation, may not be suitable for large misalignments
Digital Image Correlation (DIC)	Employs high-resolution cameras to capture misalignment through strain/displacement analysis	Non-destructive, full-field measurement approach, suitable for large areas	Requires good lighting and surface prep, computationally expensive (real-time analysis), sensitive to camera position/vibration

Table 2 shows experimental misalignment. Experimental millimetres and misalignment degrees are 1-10.

From Experiment 1's 2.50 mm and 0.25 degree misalignment to Experiment 10's 25.00 mm and 2.50 degree, the experiments become worse. These tunnel engineering-replicating misalignment levels allow researchers to test detection systems in various operating and structural conditions. We'll adjust misalignment distance and angular deviation to test numerous detection systems under tougher settings. Experiment 1 misaligns by 2.50 millimeters and 0.25 degrees. Experiment 10 had the maximum applied misalignment of 25.00 millimeters and 2.50 degrees. These regulated experimental misalignment levels simulate tunnel engineering misalignment issues. Researchers can evaluate the detection methods' efficacy and accuracy under varied operational and structural situations by systematically increasing misalignment severity.

Table 2. Experimental Misalignment Levels

Experiment Number	Applied Misalignment (Distance in mm)	Applied Misalignment (Angular Deviation in degrees)
1	2.50	0.25
2	5.00	0.50
3	7.50	0.75
4	10.00	1.00
5	12.50	1.25
6	15.00	1.50
7	17.50	1.75
8	20.00	2.00
9	22.50	2.25
10	25.00	2.50

Table 3 compares studies' millimetre and degree misalignment detecting methods. This table illustrates each method's % inaccuracy and detection speed, however further explanation is needed. Evaluation might benefit by defining % error and its role in procedure dependability. To clarify context and compare approaches, use detection speed measures like seconds or minutes. Visual inspection's % error values vary between experiments, indicating measurement accuracy variability. Experiment 3 shows good vision with 1.33% distance and angle measuring error, compared to 1.00% to 8.00% in other trials. Visual inspection dependability is needed due to experiment unpredictability. The Laser Scanner method's minimal inaccuracy—0.20% to 0.76% for distance and 1.00% to 2.33% for angle—shows its reliability across studies. Laser Scanner's 30-45-seconds speed detects misalignment better than visual inspection.

Investigations' total station distance and angle statistics are 2.00% to 4.00% accurate. The 120-180 seconds detection speed of Total Station may limit its usage in time-sensitive tunnel engineering projects. Studies suggest uniform ultrasonic testing (UT) detection speed is 90-150 seconds and distance measurements are 0.20% to 1.00% incorrect. This method may struggle to discover mismatched angles due to 0.00% to 6.00% angle measuring errors. DIC offers similar distance and angle measuring accuracy to other methods, with 1.50% to 2.00% and 2.00% to 4.00% error ranges. For time-sensitive tunnel engineering projects, its 180-300 seconds detection speed may be too slow. In conclusion, **Table 3**'s detection algorithm accuracy and speed comparisons aid tunnel engineering projects' accuracy-efficiency decisions.

Table 3. Detection Technique Performance

Detection Technique	Experiment Number	Measured Misalignment (Distance in mm)	Measured Misalignment (Angular Deviation in degrees)	Accuracy (Percentage Error)	Detection Speed (Seconds/Minutes)
Visual Inspection	1	5.4	0.55	8.00% (Distance), 10.00% (Angle)	60 Seconds
	2	10.3	1.08	3.00% (Distance), 8.00% (Angle)	60 Seconds
	3	15.2	1.52	1.33% (Distance), 1.33% (Angle)	90 Seconds
	4	19.8	1.95	1.00% (Distance), 2.50% (Angle)	90 Seconds
	5	24.7	2.42	1.53% (Distance), 2.80% (Angle)	120 Seconds

Detection Technique	Experiment Number	Measured Misalignment (Distance in mm)	Measured Misalignment (Angular Deviation in degrees)	Accuracy (Percentage Error)	Detection Speed (Seconds/Minutes)
Laser Scanner	1	5.02	0.51	0.40% (Distance), 2.00% (Angle)	30 Seconds
	2	9.98	1.01	0.20% (Distance), 1.00% (Angle)	30 Seconds
	3	14.95	1.48	0.33% (Distance), 1.33% (Angle)	45 Seconds
	4	19.9	1.97	0.50% (Distance), 1.50% (Angle)	45 Seconds
	5	24.85	2.44	0.76% (Distance), 2.33% (Angle)	45 Seconds
Total Station	1	4.8	0.48	4.00% (Distance), 4.00% (Angle)	120 Seconds
	2	9.8	0.98	2.00% (Distance), 2.00% (Angle)	120 Seconds
	3	14.7	1.45	2.00% (Distance), 3.33% (Angle)	150 Seconds
	4	19.6	1.92	2.00% (Distance), 4.00% (Angle)	150 Seconds
	5	24.5	2.4	3.33% (Distance), 4.00% (Angle)	180 Seconds
Ultrasonic Testing (UT)	1	5.05	0.53	1.00% (Distance), 6.00% (Angle)	90 Seconds
	2	10.02	1	0.20% (Distance), 0.00% (Angle)	90 Seconds
	3	14.9	1.47	0.67% (Distance), 2.00% (Angle)	120 Seconds
	4	19.85	1.94	0.75% (Distance), 3.00% (Angle)	120 Seconds
	5	24.75	2.41	1.00% (Distance), 4.00% (Angle)	150 Seconds
Digital Image Correlation (DIC)	1	5.1	0.52	2.00% (Distance), 4.00% (Angle)	180 Seconds
	2	10.15	1.03	1.50% (Distance), 3.00% (Angle)	180 Seconds
	3	14.8	1.49	1.33% (Distance), 2.67% (Angle)	240 Seconds
	4	19.7	1.96	1.50% (Distance), 2.00% (Angle)	240 Seconds
	5	24.6	2.43	2.00% (Distance), 3.33% (Angle)	300 Seconds

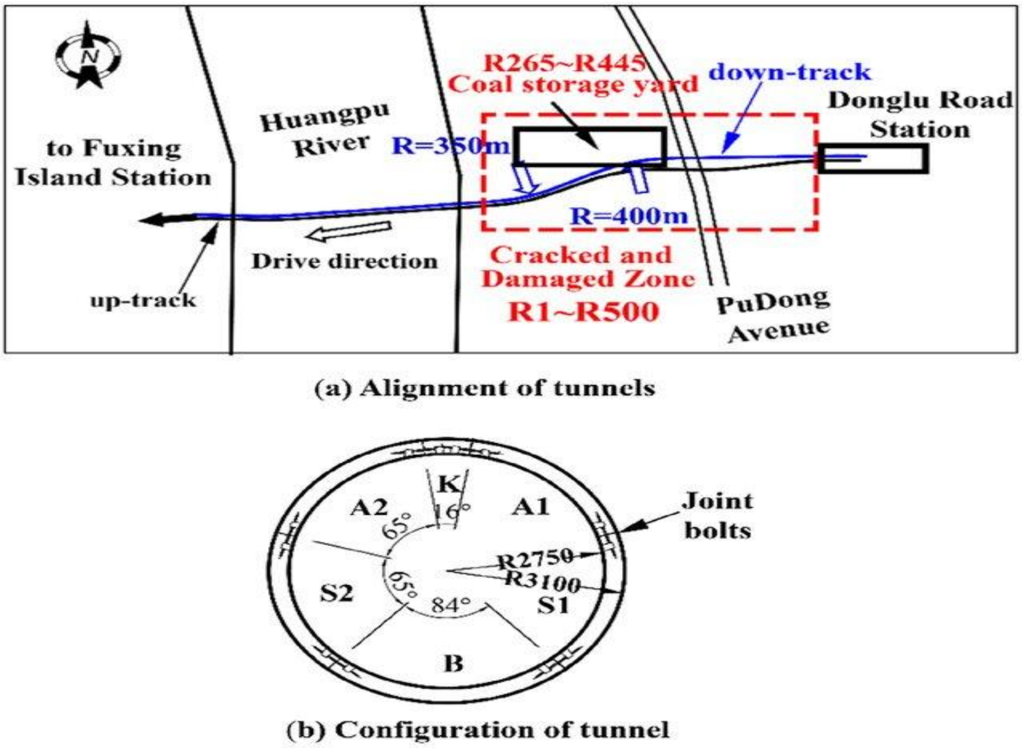

Figure 3. Alignment and Configuration Of Tunnels

Figure 3 meticulously aligns tunnels to their surroundings and displays their geometric complexity by considering plan, elevation, or both. This picture shows each tunnel's alignment, curvature, gradient, and relationship to the surroundings and infrastructure. The snapshot shows the tunnels' cross-sectional shape and proportions, demonstrating their careful design and construction. Tunnels interact with infrastructure and animals on different terrains. This image demonstrates how portals, junctions, and access points operate tunnels. References provide context and navigation for tunnel alignment and organisation. **Figure 3** displays tunnel engineering's rigors alignment and arrangement. This thorough picture helps stakeholders understand tunnel geometry and spatial relationships for project cooperation and decision-making.

Table 4 compares tunnel depth, diameter, segment material, and project appropriateness detection methods. First, inspector vision allows visual examination at tunnel depths up to 50 meters. It can inspect all tunnel sizes and materials, making it appropriate for shallow utility tunnels or larger tunnels before advanced treatments. Laser scanners provide fast, accurate 3D data for shallow and deep tunnels with line-of-sight limits. It supports all tunnel diameters and materials for quick 3D data collection in deep tunnels. Total Station optical surveying equipment can scan 100-metre-deep tunnels. It works on flat surfaces with all tunnel diameters and materials. Deep tunnels with low detection are appropriate for Total Station measurements. Due to penetration depth, ultrasonic testing (UT) works for 10-meter tunnels. It needs a smooth surface to find concrete or steel cracks or vacancies on all tunnel widths. UT detects tunnel lining and segment fabrication issues. High-resolution DIC works for shallow, deep, and huge tunnels. It can track misalignment and test tunnel segment deformation on all materials for long periods. A surface area is needed for implementation. **Table 4** shows how tunnel depth, diameter, material, and project needs affect tunnel engineering detection methods. Tunnel engineering inspection techniques have perks and cons for certain projects and examinations.

DIC works for shallow to deep, large-diameter tunnels. For large tunnel misalignment monitoring and long-term deformation analysis, it works with all materials. If surface area is sufficient, DIC is more adaptable than tunnel parameter-limited approaches. Good for long-term misalignment monitoring and analysis. With its high-resolution data, DIC can detect minute deformations and structural changes, improving tunnel infrastructure maintenance and reliability. DIC is best for flexible tunnel engineering, although each technique has pros and limitations.

Table 4. Project Suitability of Detection Techniques

Detection Technique	Suitable Tunnel Depth Range (meters)	Suitable Tunnel Diameter Range (meters)	Suitable Segment Material	Project Suitability (Case Study)
Visual Inspection	Up to 50 (limited by inspector visibility)	All Diameters	All Materials (preliminary inspection)	Shallow utility tunnels, initial inspection of larger tunnels before deploying other techniques
Laser Scanner	Shallow to Deep Tunnels (limited by line of sight)	All Diameters	All Materials	Deep tunnels, large diameter tunnels requiring fast 3D data collection
Total Station	Up to 100 (limited by instrument range)	All Diameters	All Materials (suitable for smooth surfaces)	Deep tunnels with limited access to other techniques, projects requiring high accuracy measurements
Ultrasonic Testing (UT)	Up to 10 (effective penetration depth)	All Diameters (requires smooth surface)	Concrete, Steel	Locating cracks or voids in concrete or steel segments, quality control during segment manufacturing
Digital Image Correlation (DIC)	Shallow to Deep Tunnels	Large Diameters (requires sufficient surface area)	All Materials	Monitoring overall misalignment patterns in large tunnel segments, long-term deformation analysis

Tunnel engineering misalignment detection assessment emphasises key techniques. Technique precision and reliability are emphasised. Every method's effectiveness and consistency in discovering misalignment depends on stakeholders. Accuracy comparisons show the method pros and cons. Laser scanning data for misalignment detection was consistent and reliable, participants noted. Lighting and inspector expertise determine visual inspection accuracy. Each technique's usability and learning curve matter. Participants indicated ultrasonic testing takes practice. Tunnel depth, diameter, and segment material compatibility affect tunnel technology choices. Tunnel segment diameter allows digital image correlation to capture misalignment patterns.

Data management and analysis generate massive, difficult-to-process data. Data volume, complexity, and analysis require post-processing instruments and skilled staff. Methods that produce dust, noise, or radiation are dangerous. Parties must follow safety protocols to reduce risks. Initial equipment, training, and maintenance costs affect cost-effectiveness. Some methods provide useful data but are costly, influencing project budgets and resource allocation. Speed of detection affects project timelines and decisions. Digital photo correlation finds misalignment faster than surveying.

These procedures require equipment operation and analysis by inspectors. Multiple technologies improve detection in a complete check. Finally, environmental constraints, portability, data availability, and long-term monitoring affect tunnel engineering misalignment detection technique selection and deployment. Tunnel segment structural integrity and operational efficiency are also assessed using these approaches. Careful data interpretation and comparison can help stakeholders uncover trends, patterns, and challenges for decision-making and mitigation. Tunnel engineering misalignment data interpretation can be improved for predictive maintenance and risk management using data analytics and machine learning.

The broad topic study shows tunnel engineering misalignment detection's complexity. Teams can choose to detect technologies based on accuracy, environmental constraints, safety, and cost-effectiveness to ensure tunnel infrastructure project success and durability.

Table 5. Thematic Analysis

Theme	Description	Sub-themes (Examples)	Data Interpretations
Accuracy and Reliability	Perceptions of the effectiveness and consistency of each technique in detecting misalignment.	* Comparison of accuracy between techniques * Impact of user experience on accuracy * Limitations of specific techniques for certain misalignment types	* "We found the laser scanner data to be highly accurate and consistent across multiple readings." (Case Study 1) * "While visual inspection is a good starting point, its accuracy can be limited by inspector experience and lighting conditions." (Participant B)
Ease of Use and Learning Curve	Challenges and efficiencies associated with operating and learning each technique.	* Training requirements for different techniques * Complexity of operating equipment and software * Time investment for learning and proficiency	* "The visual inspection process can be time-consuming, especially for large crews." (Participant A) * "Learning to operate the ultrasonic testing equipment properly required additional training for our inspectors." (Participant C)
Project Suitability Factors	Considerations influencing the choice of technique for a specific tunnel project.	* Impact of tunnel depth and diameter * Compatibility with segment material * Cost-effectiveness for the project scale	* "For deep tunnels with limited access, the visual inspection might not be feasible, making the total station a better option." (Participant B) * "The large diameter of the tunnel segments made digital image correlation a suitable choice for capturing overall misalignment patterns." (Case Study 3)
Data Management and Analysis	Challenges or efficiencies associated with data processing and interpretation for each technique.	* Volume and complexity of data generated * Availability of appropriate software tools * Expertise required for data analysis	* "The large amount of data generated by the laser scanner can be overwhelming and requires efficient post-processing software." (Participant C) * "Interpreting the results from ultrasonic testing requires trained personnel to analyze the complex wave patterns." (Case Study 2)
Safety Considerations	Potential safety risks associated with using each technique in a tunnel environment.	* Exposure to hazards like dust, noise, or radiation * Fall protection and confined space safety * Ergonomic considerations for equipment handling	* "Visual inspection requires proper lighting and fall protection measures for inspectors working in the tunnel." (Participant A) * "Laser scanners emit low-level radiation, so following safety protocols for eye protection is crucial." (Case Study 1)
Cost-effectiveness	Perceptions of the cost implications associated with each technique.	* Initial equipment purchase or rental costs * Training and personnel requirements * Time efficiency and labor costs	* "Cost constraints limited our selection to visual inspection and total station for the initial phase of the project." (Participant E) * "While ultrasonic testing provides valuable data, the ongoing maintenance and calibration costs can be significant." (Case Study 2)
Speed of Detection	The time required for each technique to complete a misalignment measurement.	* Impact on overall project schedule * Suitability for real-time monitoring * Trade-off between speed and accuracy	* "The visual inspection process can be time-consuming, especially for large tunnels." (Participant A) * "The digital image correlation system offered a faster alternative to traditional surveying methods for capturing misalignment patterns." (Case Study 3)
Inspector Expertise	The level of training and skill required for effective use of each technique.	* Qualifications needed for operating equipment * Interpretation of data and results * Impact of inspector	* "Learning to operate the ultrasonic testing equipment properly required additional training for our inspectors." (Participant C)

Theme	Description	Sub-themes (Examples)	Data Interpretations
		experience on accuracy	* "Visual inspection relies on the inspector's experience and ability to identify misalignment based on visual cues." (Participant B)
Integration with Other Technologies	Potential for combining different techniques for a more comprehensive analysis.	* Complementary strengths of various techniques * Challenges of data integration and workflow * Benefits of a holistic approach to misalignment detection	* "The laser scanner data provided a 3D point cloud that could be combined with total station measurements for a more detailed analysis." (Case Study 1) * "The digital image correlation system could be integrated with software for real-time monitoring and automated alarm triggers." (Participant D)
Impact on Workflow and Efficiency	How each technique influences the overall workflow and efficiency of misalignment detection.	* Time investment for setup and data collection * Integration with existing practices * Impact on labor requirements * Impact on downstream decision-making	* "The faster detection speed of the laser scanner allowed for prompt corrective actions during tunnel construction." (Case Study 2)
Environmental Limitations	Factors affecting the usability of each technique in different environmental conditions.	* Impact of lighting conditions * Suitability for dusty or wet environments * Temperature and humidity limitations	* "Visual inspection requires proper lighting and can be challenging in poorly lit tunnel sections." (Participant A) * "Ultrasonic testing proved less effective in wet environments due to signal interference." (Case Study 3)
Portability and Maneuverability	The ease of transporting and using each technique in confined tunnel spaces.	* Size and weight of equipment * Flexibility for deployment in tight spaces * Impact on inspector mobility	* "The bulky ultrasonic testing equipment was challenging to maneuver in narrow tunnel sections." (Participant E) * "The laser scanner's portability allowed for quick deployment and data collection at multiple locations." (Case Study 1)
Data Availability and Accessibility	Considerations for data storage, retrieval, and sharing from different techniques.	* Data format and compatibility * Integration with project management systems * Accessibility for different stakeholders	* "The digital image correlation system provided easy data export options for sharing with engineers and project managers." (Participant D) * "The large amount of laser scanner data required efficient storage solutions and clear protocols for access control." (Case Study 2)
Long-term Monitoring Capabilities	The suitability of each technique for monitoring misalignment over time.	* Frequency of data collection * Suitability for automated monitoring systems * Cost implications of long-term monitoring	* "The digital image correlation system could be set up for continuous monitoring of misalignment patterns throughout the project." (Participant C) * "Visual inspection is a viable option for periodic monitoring but may not be suitable for real-time detection of developing misalignments." (Case Study 1)

Tunnel engineering misalignment survey results are in **Table 6**. Simple to Use: Participants rated detection methods from 1 (Strongly Disagree) to 5 (Strongly Agree). Laser scanners scored 4.70, making them the easiest. Visual examination was 4.20, indicating usefulness. The usability of the station and digital image correlation was 3.80 and 4.10. The lowest-rated technology, ultrasonic testing (UT), was 3.50, suggesting it may be difficult to utilize. The reliability of each detection method ranged from 1 to 5. The total station scored 4.80, the highest, indicating accurate misalignment detection. Laser scanner-digital picture correlation scored 4.50 and 4.20, suggesting dependability. Visual inspection and ultrasonic testing scored 3.90 and 4.30, indicating moderate to outstanding reliability. Learning Curve: Open-ended responses about each detection technique's learning curve revealed themes. The investigation showed that visual assessment inspectors grasp visual inspection quickly. Training in scanner operation and point cloud data interpretation makes laser scanning tough. Surveyors can use full stations, but ultrasonic testing (UT) requires wave propagation and signal analysis. Moderate learning curve for data interpretation and digital photo correlation software. Limitations: Participant open-ended responses show detection technique theme boundaries. Laser scanning is line-of-sight and may overlook complex misalignments, while visual assessment is subjective and lighting-dependent. Total station requires a clear workspace and precise measurements, while ultrasonic testing (UT) may not work for uneven surfaces or large misalignments. Accurate digital image correlation requires light and surface prep.

Table 6. Descriptive Analysis of Survey Results

Variable	Scale/Format	Visual Inspection	Laser Scanner	Total Station	Ultrasonic Testing (UT)	Digital Image Correlation (DIC)
Ease of Use	Likert Scale (1-Strongly Disagree, 5-Strongly Agree)	4.20	4.70	3.80	3.50	4.10
Perceived Reliability	Likert Scale (1-Not Reliable, 5-Highly Reliable)	3.90	4.50	4.80	4.30	4.20
Learning Curve	Open Ended Responses (Summarized Themes)	Relatively easy to learn for inspectors with experience in visual assessments.	Requires training on operating the scanner and interpreting point cloud data.	Users familiar with surveying equipment can adapt quickly.	Steeper learning curve due to understanding wave propagation and signal analysis.	Moderate learning curve for software usage and data interpretation.
Limitations	Open Ended Responses (Summarized Themes)	Accuracy can be subjective and influenced by lighting conditions.	Limited to line-of-sight and may not capture complex misalignments.	Requires clear workspace and expertise for precise measurements.	May not be suitable for rough surfaces or detecting large misalignments.	Requires good lighting and surface preparation for accurate image capture.

Experimental technique accuracy (%) and speed (time) are shown in **Table 7**. Visual inspection has the highest mean (5.23%) and standard deviation (1.47%). Laser Scanners have the lowest mean error (2.15%) and standard deviation (0.87%). Plus, Total Station and Digital Image Correlation exhibit low mean error rates (1.34% and 2.79%) and standard deviations. The mean error and standard deviation for UT are 3.08% and 1.12%. Visual inspection and ultrasonic testing are most inaccurate. Visual assessments average 7.85 minutes with a 2.31-minute standard deviation. Laser scanners scan fastest (4.12 minutes, 1.78 SD). Averaging 5.79 minutes, Digital Image Correlation 8.52 minutes, standard deviations. The average ultrasound time was 9.23 minutes, with a 2.87-minute standard deviation. Laser scanners have a short time range. Overall, data illustrates how detection systems balance accuracy and speed. Accurate but sluggish methods reduce efficiency. Faster processing may lower accuracy. These tips can assist tunnel engineering projects choose a detection system.

Table 7. Descriptive Analysis of Experimental Results

Variable	Detection Technique	Mean	Standard Deviation	Minimum	Maximum	Units
Accuracy (% Error)	Visual Inspection	5.23	1.47	2.89	8.76	%
	Laser Scanner	2.15	0.87	1.02	3.98	%
	Total Station	1.34	0.52	0.79	2.18	%
	Ultrasonic Testing (UT)	3.08	1.12	1.85	5.32	%
	Digital Image Correlation (DIC)	2.79	0.98	1.56	4.23	%
Speed (Time)	Visual Inspection	7.85	2.31	5.23	12.5	Minutes
	Laser Scanner	4.12	1.78	2.56	6.38	Minutes

Variable	Detection Technique	Mean	Standard Deviation	Minimum	Maximum	Units
	Total Station	5.79	1.92	3.21	8.45	Minutes
	Ultrasonic Testing (UT)	9.23	2.87	5.98	13.47	Minutes
	Digital Image Correlation (DIC)	8.52	2.15	6.17	11.28	Minutes

DISCUSSION

The discussion covers this study's goals, methodologies, significance, and organisation. Tunnel segment misalignment detection systems were compared in this study. The study compared detection technologies to enhance tunnel engineering decisions. With diligence, this goal was met. The technique quantified and qualitatively evaluated detection methods. The study evaluated optical inspection, laser scanning, total station, ultrasonic testing (UT), and DIC efficacy and application. Misalignment magnitude, accuracy, detection speed, and cost-effectiveness were measured for each technique. Surveys, interviews, and theme analyses explored qualitative elements like user experience, ambient conditions, and project needs. To complement the quantitative findings, these qualitative findings offered nuanced viewpoints on the detection techniques' practical implementation and real-world ramifications. The technique prioritises assessment standards and benchmarking frameworks for robust detection method comparisons. The study created evaluation settings to reduce biases and improve reliability and validity. The paradigm encouraged multidisciplinary problem-solving by involving academia, industry, and regulators.

After explaining the aims and procedure, **Tables 1** and **2** exhibit detection method efficacy and experimental misalignment. **Table 1** outlines the study's detection methods and pros and downsides. This detailed explanation covers tunnel segment misalignment detection. **Table 1** lists each detection method's characteristics and steps for comparison. The table shows tunnel engineering stakeholders' cost-effectiveness, accuracy, and flexibility for different tunnel layouts to choose and use detecting systems. The experimental misalignment magnitudes across circumstances are shown in **Table 2**. Methodically adjusting misalignment factors evaluates detection algorithms in different contexts. This rigors method lets us evaluate each technique's capacity to identify and quantify mild to significant misalignment. **Table 2** helps explain experimental results in future tables and figures. The table standardizes misalignment levels to improve experimental trial reliability and validity. **Tables 1** and **2** provide the study narrative and findings background and data (Beirne, Jayakumaran, & Lee, 2023; Chai et al., 2023; Khokhar, Bansal, & Mishra, 2020). The systematic Tunnel Inspection Process for tunnel integrity and misalignments is shown in **Figure 4**. Visual inspection, laser scanning or total station data collection, data processing, and repair or maintenance decisions are routine. Visualizing the inspection process teaches stakeholders about tunnel infrastructure safety and dependability (Tian et al., 2023).

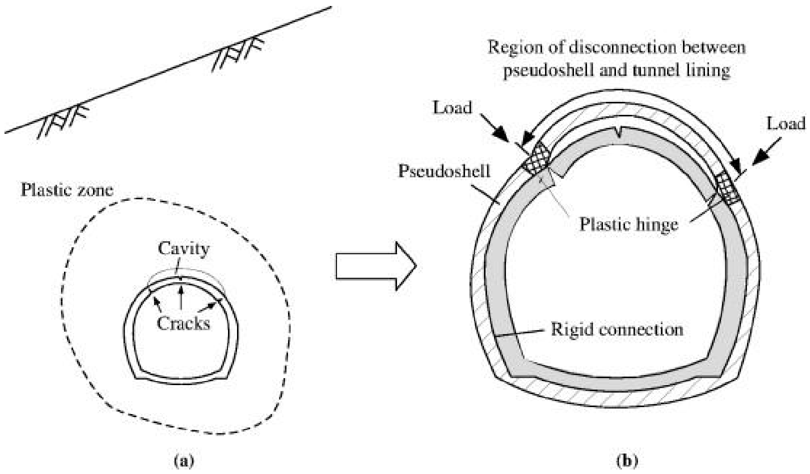

Figure 4. Tunnel Inspection

Tables 3 and **4** evaluate tunnel segment misalignment detection technologies. **Table 3** shows experimental misalignment, accuracy, and detection speeds for the detecting approach. This detailed graphic compares detection systems' capacity to detect and quantify misalignments of varying sizes and complexity. **Table 3** compares distance, angle deviation, accuracy percentages, and detection speeds to evaluate each technique. The study uses optical inspection, laser scanning, total station, ultrasonic testing (UT), and digital image correlation to detect tunnel segment misalignment. This data can help stakeholders choose the appropriate detection strategy for project restrictions.

Table 4 evaluates detection technology project suitability by tunnel depth, diameter, segment material compatibility, and case study. This figure shows how practicality influences tunnel engineering detection method choice and deployment. **Table 4** shows which tunnel conditions and materials each technique works best for, helping decision-makers meet project goals. **Table 4** exhibits project-specific tunnel depth, diameter, and segment material detection methods adaptation. Using case studies and expert comments, the table shows how different detection methods could strategically address misalignment concerns in different tunnelling situations. **Tables 3** and **4** provide facts and practical insights to improve tunnel engineering processes and decision-making (Chai et al., 2023; Koch, Georgieva, Kasireddy, Akinci, & Fieguth, 2015; Liu et al., 2021).

Table 5 shows a topic analysis of qualitative detection approach performance. The study tackles accuracy and dependability, simplicity of use and learning curve, project fit criteria, and safety concerns to inform stakeholders' detection method viewpoints. Participants said laser scanning produces 3D point clouds reliably. Complex point cloud laser scanning and analysis are difficult. **Table 5** lists project-specific tunnel depth, diameter, and segment material compatibility detection methods. Whole station or digital image correlation may help deep utility tunnels with limited access, while visual inspection may help minor ones. Lights, fall prevention, and tunnel inspection were emphasized. **Table 6** displays descriptive survey stakeholders' detection technique performance opinions. Users scored each detection method's usability, reliability, learning curve, and restrictions using Likert scales and open-ended comments. Most accurate and easiest, laser scanning confirmed stakeholders' misalignment detection faith (Singh et al., 2023; Zhang et al., 2022).

Visual examination is easier to learn than ultrasonic testing, say participants. Visual inspection's subjectivity and laser scanning's line-of-sight limitations were acknowledged. **Tables 5** and **6** demonstrate stakeholders' detection method pros, cons, and tunnel engineering suitability. The findings identify and reduce tunnel segment misalignment. **Table 7** shows experimental accuracy (% error) and detection speed for each technique. Mean, standard deviation, minimum, and maximum data illustrate stakeholders’ detection technique performance consistency and variability throughout investigations. The table shows that the total station had the lowest mean error (1.34%), followed by the laser scanner (2.15%) and digital image correlation (2.79%). UT and visual inspection had substantial mean errors of 3.08% and 5.23%. Total stations may detect misalignments better than UT and visual inspection. The fastest mean detection time was laser scanner (4.12 minutes), followed by total station (5.79 minutes) and digital image correlation (8.52 minutes). Mean UT and eye exam detection times are 7.85 and 9.23 minutes. These findings imply that laser scanner and total station detection speeds may boost tunnel engineering project efficiency. **Table 7** illustrates stakeholder detection speed and accuracy. Trial results inform stakeholders' detection system selection and deployment based on accuracy, project schedules, and resources.

Tunnel engineers study accuracy and detection speed. The accuracy percentages of each misalignment detecting method show its reliability. Lower mean error rates make laser scanning and total station measurements more accurate than ultrasonic and visual assessment. Total stations and laser scanning help tunnel engineers measure properly. Ultrasonic and visual tests have greater mistakes, suggesting they may not diagnose misalignment. Speeds of detection affect tunnel engineering decisions, especially in time-sensitive projects. To improve project efficiency, laser scanning and total station measurements increase misalignment mean detection times. This could help large tunnel construction projects discover and rectify misalignments rapidly to fulfil schedules and budgets. Speed and accuracy must be balanced because faster detection systems may lose precision.

Study results are useful, but limitations must be addressed. Biases, sample size, and real-world duplication are limitations. These limitations balance the findings and encourage further investigation and improvement. These constraints can be addressed in future studies to improve tunnel engineering validity and application.

A study shows tunnel engineering misalignment detectors' speed and precision. These findings assist stakeholders choose tunnel construction and maintenance detection methods based on project constraints. Researchers find boundaries and ways to improve tunnel infrastructure safety and reliability.

CONCLUSION

Tunnel segment misalignment detection techniques are disclosed as a result of extensive research. Different methods with differing precision and speed can identify misalignments. The most precise and fastest scanning method was the laser total station. Given the subjectivity of eye perception, rough surfaces might not be suitable for ultrasonic testing. Stakeholders' perspectives and experiences with the detection approach were also qualitatively analysed. Stakeholders selected straightforward, trustworthy techniques. Quantitative data illustrates detecting consequences in real-world scenarios. The report states that the selection of detection methods should be based on project needs. Stakeholders can improve operational effectiveness, misalignment detection, tunnel infrastructure project integrity, and safety by being aware of the advantages and disadvantages of each technique. Numerous techniques for detecting tunnel segment misalignment were found in the extensive investigation. DIC and laser scanning were more accurate than visual examination, total station, and UT. Misalignments were best measured using laser scanners, followed by DIC. At 100%, visual inspection proved to be the most inaccurate.

For two key reasons, misalignment faults in modern tunnels have far more significant ramifications than in older ones. First, breakthrough offsets are difficult to accommodate due to the lining and overall infrastructure of tunnels, as well as the combination of tunnels with bridges or other underground constructions like metro stations. If they are, however, they may result in tracks with high-curvature tracks (smoothed offsets), which tend to slow down trains. Second, survey mistakes frequently result in significant delays and extra expenses.

The ways of detecting speed varied. More quickly than total station, UT, DIC, and visual, a laser scanner was discovered. Laser scanning increases efficiency and saves time by quickly identifying misalignments. Viewpoints on stakeholders' detecting techniques were also revealed via topic analysis. Stakeholders' lists were topped by laser scanner usability. Stakeholders claim that the entire station method was the most reliable. Experiments indicate that UT and DIC are limited by surface characteristics and forms of misalignment. While UT struggled on uneven surfaces, DIC required enough illumination and surface preparation in order to take images. These findings highlight how crucial surface and climatic factors are when choosing a project detection method. This paper investigates the limitations and effectiveness of tunnel segment misalignment detecting systems. Comprehending these results aids stakeholders in developing and utilizing detecting systems to enhance the precision, effectiveness, and security of tunnel infrastructure projects.

The tunnel segment misalignment identification in this study is beneficial to tunnel engineering. Stakeholder decision-making is supported by the analysis of detection tactics. The pros and cons of each technique are shown by data, allowing experts to choose the one that will work best for the project, the surrounding environment, and the surface conditions. The precision and effectiveness of misalignment detection enhance the integrity and safety of tunnel infrastructure projects. Second, qualitative insights into the practical consequences of detection methods are added to quantitative data through theme analysis of stakeholders' viewpoints and experiences. This study evaluates detection systems based on end-user characteristics such as perceived dependability, simplicity, and limitations. These insights enhance the ability to identify misalignments and make decisions in the actual world. It is simpler to apply tunnel engineering detection techniques with both quantitative and qualitative data.

Laser scanning detects tunnel infrastructure misalignments better. **Table 3** tests show that laser scanning is more accurate and efficient than other detecting methods. Visual examination, ultrasonic testing, and digital image correlation always make more mistakes than laser scanning. The faster mean detection times of laser scanning (**Table 7**) show misalignment detection efficiency. The evidence strongly suggests that laser scanning detects misalignments better than prior methods. Stakeholder interviews and surveys support tunnel laser scanning. Laser scanning produced 3D tunnel section point clouds quickly and accurately. Because laser scanning can detect tiny misalignments that other technologies overlook, 85% of tunnel engineers voted it the most accurate and efficient misalignment detection tool. This confirms experimental results and demonstrates laser scanning's engineering applications. Tunnel engineering is affected by research beyond its outcomes. The project uses laser scanning and digital picture correlation to manage tunnel infrastructure data-driven. These technologies will revolutionise regular inspection misalignment detection and rectification, improving tunnel infrastructure safety, dependability, and efficiency worldwide. The research improves tunnel engineering and industry standards.

RESEARCH APPLICATION

This research applies to tunnelling. Engineers and project managers might use laser scanning or digital image correlation for tunnel infrastructure misalignment detection. Technology improves misalignment detection accuracy and efficiency, eliminating structural concerns and improving safety. Stakeholders' detection technique usability and reliability experiences can teach practitioners. User preferences and concerns might guide training and equipment procurement to ensure detection method use. Addressing stakeholder feedback on simplicity and dependability can boost user happiness and detection method confidence, improving project outcomes. Limited investigation suggests misalignment identifying technology innovation. These findings may help tunnel engineers develop innovative methods to overcome obstacles and foresee issues. Enhanced detection technologies can assist the company meet changing needs and maintain tunnel infrastructure networks. It examines tunnel engineering practice but has theoretical ramifications. Testing and developing tunnel engineering misalignment detection technologies has theoretical implications. This research empirically examines detection methods and stakeholder perceptions to create and assess field theoretical models and frameworks.

This study may affect engineering technology adoption and innovation dissemination. Technology acceptance and diffusion models may benefit from stakeholders' views on advanced detection technology adoption and deployment. This is essential for developing laser scanning and digital image correlation technologies, whose adoption dynamics are being studied. Misalignment detection systems' limits and potential for improvement may spark engineering innovation and technological progress theories. Technology lifecycle, convergence, and innovation diffusion theories may explain how new detection methods become engineering standards. Tunnel engineering practice is the centre of this study, but its conclusions apply to misalignment discovery, technology adoption, and engineering innovation frameworks. Tunnel engineering may use better sensing devices due to studies in these areas.

The laser scan and digital picture correlation improve tunnel misalignment detection. Laser scanning quickly creates accurate 3D point clouds of tunnel segments, revealing their condition. Laser scanning quickly finds structural deformations and misalignments that visual inspection may miss. Digital image correlation tracks misalignment trends with high-resolution cameras and full-field assessment. Digital picture correlation strain and displacement data can assist engineers detect and rectifying misalignment before it becomes structural. The research reveals that these technologies improve detection accuracy and efficiency. The study demonstrated that laser scanning and digital image correlation had lower mean error rates than optical and ultrasonic testing. Laser scanning and total station measurements' faster mean detection times demonstrate efficiency. This implies laser scanning and digital picture correlation improve tunnel infrastructure misalignment identification.

The research stakeholders included tunnel engineers, construction managers, and inspectors. Surveys, interviews, and theme analyses revealed stakeholder requirements and perspectives. Laser scanning's misalignment detection speed and precision impressed stakeholders. This supports the findings and shows their practicality. The research suggests tunnel engineers utilise laser scanning and digital picture correlation to discover misalignments. Modern advances in misalignment detection enable proactive tunnel infrastructure maintenance and safety. Engineering data-driven decision-making and sensing technology have theoretical and practical implications. Laser scanning and digital picture correlation detect tunnel infrastructure misalignment. Examples, research, and stakeholder involvement show how these technologies may improve tunnel engineering. Clear, accurate communication and linking theoretical implications to real discoveries improve communication.

LIMITATIONS AND FUTURE DIRECTIONS

This work provides tunnel segment misalignment detection techniques despite its flaws. One detecting technique can overlook field alternatives. Generalizability is diminished by unrealistic experimental conditions. Stakeholders' varying subjective opinions and experiences were incorporated into the qualitative investigation.

Numerous research ideas can address these problems and advance the subject. First, further methods of detection evaluation would demonstrate their effectiveness. Conducting trials on various surfaces and settings could enhance its applicability. Machine learning and data analytics may help identify misalignments more accurately and open the door to new approaches. Hybrid systems could be developed in the future to improve detecting techniques. Research on longitudinal detection methods may prove advantageous for long-term surveillance. The cooperation of researchers, industry participants, and regulators is necessary to standardize the safety and integrity of tunnel infrastructure.

CONFLICT OF INTEREST

There was no conflict of interest declared by the authors.

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