CHAPTER 86

Integrating Drone Technology, GIS, and Digital Twins for Enhanced Pothole Management: A Sustainable Approach to Infrastructure Maintenance

Chaitali Shelke[1]

ABSTRACT

The increase in traffic volume accelerates the depreciation of the road infrastructure, which in turn has an adverse effect on the overall road performance and safety. Manual road assessments are particularly poor in accuracy and the depth of fault analysis, thus traditional methods are not capable of supporting these tasks adequately. This research provides a solution in the form of a complete methodology that employs Digital Twin Technologies, photogrammetry using drones, and Geographic Information Systems (GIS) to construct the assessment of the state of the road infrastructure to be as comprehensive as possible regarding defection quantification and sustainable repair techniques. The method starts with selecting segments of the road that is necessary to assess and capturing drone footage of the segments. The footage is then processed using QGIS, making it possible to find and measure imperfections such as potholes and cracks. Advanced technology such as Digital Twin enables infrastructure manager to make data-driven decisions, check assets in real-time, and perform predictive maintenance. Enhance the sustainability of repairs, materials such as Stone Matrix Asphalt are used to diminish the utilized resources while extending the life of the infrastructure. In the end, the method is rounded up with the formulation of cost estimates and optimization strategies for sustainable repairs. This research aims to streamline road maintenance operations, enhance decision-making processes, and ensure long-term infrastructure safety and sustainability by using advanced technologies in pothole management.

Keywords: Drone technology; GIS; Digital twin; Sustainable repairs; Stone matrix asphalt; Infrastructure management.

1.0 Introduction

Increasing traffic leads to faster pavement deterioration, affecting road performance and safety. Traditionally, road monitoring relies on manual inspections and specialized tools to assess surface conditions, but this process is time-consuming and prone to errors. Maintaining road infrastructure costs 0.4%–2% of the original construction cost (Mahmoodian *et al.*, 2022), making consistent maintenance essential for road longevity.

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Manual inspections, such as walking the road or conducting "windshield" surveys from vehicles, often miss hidden defects, leading to incomplete assessments.[1] Drone-based profiling with Real-Time Kinematic (RTK) technology improves road assessments by providing 3D positional accuracy within 2 cm, enhancing defect detection and enabling better synchronization through standardized coordinate systems and analysis software. (Kuttah & Waldemarson, 2024). Drone-based imaging provides an affordable and accurate way to identify surface issues like cracks, with geotagging helping to map defects precisely and GIS databases recording their type, severity, and location for better reporting and maintenance planning. (Fendi, Adam & Smith, 2024). Digital Twin Technology combines a real-world system with a computational model, enabling two-way data flow for monitoring, control, and decision-making. Its adaptability allows it to be customized for different industries based on specific needs.(Callcut *et al.*, 2021). Pothole repairs often rely on short-term cold mix fixes or more durable hot mix asphalt (HMA) repairs, but shifting to sustainable methods can reduce waste, resource use, and maintenance needs. (Chen, Wang & Venkiteela, 2023).

This project aims to improve pothole detection and management by using drone technology, GIS, and Digital Twin models. Drones capture high-resolution images, which are processed through GIS to precisely measure pothole size and location, helping to plan repairs more effectively. The Digital Twin model offers a real-time view of road conditions, allowing for better prediction and maintenance planning. By using eco-friendly materials and methods, the project enhances repair efficiency while supporting long-term road sustainability.

2.0 Related Work on Road Engineering using Digital Twin Technology

2.1 Development of digital twins for road infrastructure

Jiang *et al.* (2022): This study explores the creation of digital twins for the UK's A1(M) motorway using map data, but it faces challenges with complex road geometry, limited highway images, and inconsistent data quality. Tchana *et al.* (2019): This paper examines the use of digital twins for managing linear infrastructure, focusing on improving cost efficiency, performance, and collaboration, but highlights issues with data handling and IT system complexity. Feng Jiang *et al.* (2024): This research proposes a model for sustainable urban road planning by combining Digital Twin technology, multi-factor decision analysis (MFDA), and GIS to enhance road design and data management.

2.2 Challenges in digital twin adoption and data integration

Liu *et al.* (2024): This study introduces a framework for improving infrastructure management using multi-domain data integration but raises concerns about high costs, data security risks, and budget limitations. Macoriga *et al.* (2022): This research evaluates road network maintenance in Pisa, identifying financial constraints and recommending policy changes to enable more sustainable road management. Michaela *et al.* (2024): This study looks

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at integrating civil structural models into digital twins to enhance safety and cut costs, but faces challenges with data compatibility and lifecycle management.

2.3 Technologies supporting digital twin development

D'Amico *et al.* (2023): This study integrates subsurface imaging radars (SIR) and portable laser mapping systems (PLMS) within a construction data model to improve infrastructure analysis, but faces issues with integrating ground-penetrating radar (GPR) and missing survey data. Liu *et al.* (2023): This review outlines different methods for creating digital twins in civil infrastructure, including AI and machine learning, but notes that high computational demands and data accuracy are ongoing challenges. Talha *et al.* (2023): This study recommends cost-effective pothole patching techniques using survival analysis but acknowledges that the findings may not apply to all road types and conditions.

2.4 Decision support tools and data management

Consilvio *et al.* (2023): This study presents a virtual twin-based support system for better asset management by integrating AI with existing systems, but it highlights that the technology is still in its early stages and needs further testing. Broo *et al.* (2020): This research emphasizes the potential of AI-driven decision-making for infrastructure management but points out challenges with data handling and organizational resistance to adopting new systems.

2.5 Pothole and pavement maintenance

Talha *et al.* (2023): This study evaluates different winter pothole patching techniques and recommends the most cost-effective options based on weather and traffic conditions, but its findings are limited to specific sites. Dong *et al.* (2014): This research shows that semipermanent patches last longer than other methods, but the short evaluation period and lack of consideration for pavement conditions limit its broader applicability. Chen *et al.* (2023): This study finds that infrared heating improves asphalt patch bonding, but the results are based on artificial potholes, which may not reflect real- world traffic conditions.

2.6 Innovations in road profiling and monitoring

Kuttah *et al.* (2024): This study tests UAV-based RTK technology for gravel road profiling and finds it as accurate as traditional methods, but issues with data alignment, vegetation interference, and ArcGIS compatibility remain. Almuhanna *et al.* (2018): This research applies GIS-based planning for road preservation in Karbala, Iraq, but the reliance on manual data collection makes it difficult to use on high-traffic roads.

2.7 Sustainability and environmental considerations

Hamayde *et al.* (2021): This study uses GIS to create earthquake risk maps in Dubai, but its reliance on 2D models limits its accuracy and broader application. Khan & Kumar

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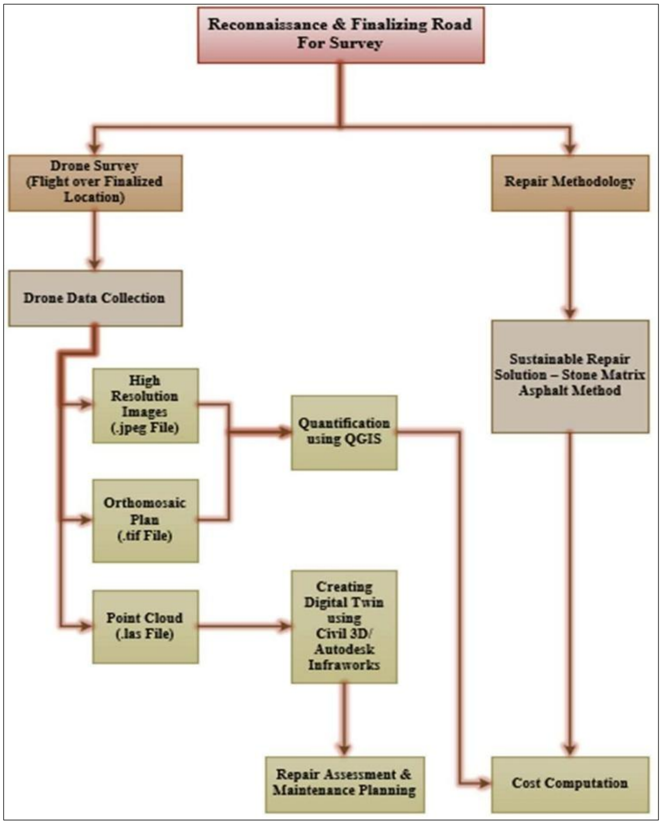
(2024): This research uses terrestrial LiDAR for 3D modeling of pavement distress, but difficulties in detecting certain distresses and high processing demands limit its efficiency.

Figure 1: Proposed Methodology



3.0 Research Methodology

By providing a systematic approach to road survey, analysis, and sustainable repair planning, this technique guarantees data-driven maintenance decision making and economic effectiveness.

- Road Selection: Roads selected based on traffic, damage, and accidents.
- Drone Survey: Drones capture high-resolution road data.
- Data Processing: QGIS maps and measures road damage.
- Digital Twin: 3D model created for repair planning.
- Sustainable Repair: SMA used for durability and longevity.
- Cost Estimation: Repair costs calculated for efficiency.
- Maintenance Planning: Data-driven plan ensures timely repairs.

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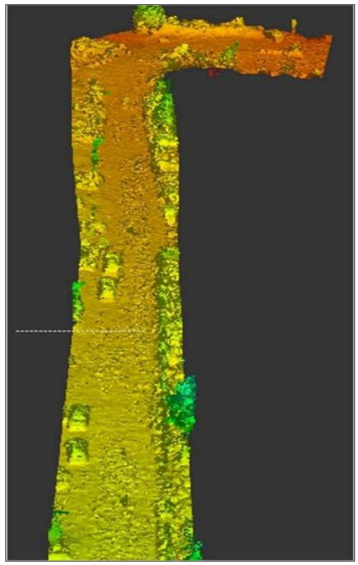
4.0 Experimental Setup

The study began with a drone survey of a 1.5-kilometer pothole-ridden road section using the DJI Mavic 3 MTK drone, equipped with an infrared sensor and an omnidirectional binocular vision sensor. To ensure full coverage, three flights were conducted over the segment, gathering detailed data to create a 3D model of the road's surface and internal structure. Road surface distress inspection, as highlighted by Barbieri & Lou (2024), plays a key role in monitoring pavement conditions and identifying construction defects, poor materials, and inadequate maintenance. The study incorporated two advanced technologies: "LiDAR", which uses laser beams to produce highly accurate surface images with a precision of 1 mm to 10 mm, and "Infrared Thermography", which captures heat emissions to create thermal images, allowing quick data collection at a rate of 30 to 60 scans per second. Refer Figure 2, 3, 4.

Figure 2: Drone View Image

Figure 3: Ariel Image

Figure 4: Infrared Image



4.1 Data processing

DroneDeploy software was used to process the drone survey data and extract it into three different forms for a thorough examination of the state of the road surface:

- *High-Resolution Images (.jpeg):* High-quality images provided clear visual data, helping to identify surface issues like cracks and potholes through detailed visual inspection.
- *Ortho Mosaic Maps (.tif):* Georeferenced maps created from stitched drone images allowed accurate measurement and spatial analysis of road defects.
- *Point Cloud Data (.las):* Dense 3D models generated from photogrammetry and LiDAR data helped assess surface imperfections and calculate the volume of road damage.

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4.2 Pothole detection and quantification

High-resolution drone images were essential for identifying potholes and road defects with pinpoint accuracy, thanks to their high spatial resolution. The images helped detect surface issues like cracks, potholes, and deformations with clarity. Ortho mosaic maps generated from the drone data were imported into QGIS (v3.34.15), where road defects were accurately mapped, measured, and referenced using historical Earth data. This integration improved the efficiency and accuracy of pavement condition assessments using GIS tools.

- *Import ortho map:* Load the georeferenced Ortho mosaic map into QGIS using UTM 84-43N CRS.
- *Digitize potholes:* Trace pothole boundaries using the "Add Polygon" tool and save as a shapefile.
- *Calculate area:* Use QGIS's Field Calculator to compute pothole area in square meters.
- *Export results:* Save the updated layer and export for analysis or reporting.

Figure 5: Pothole Tracing and Area Calculations

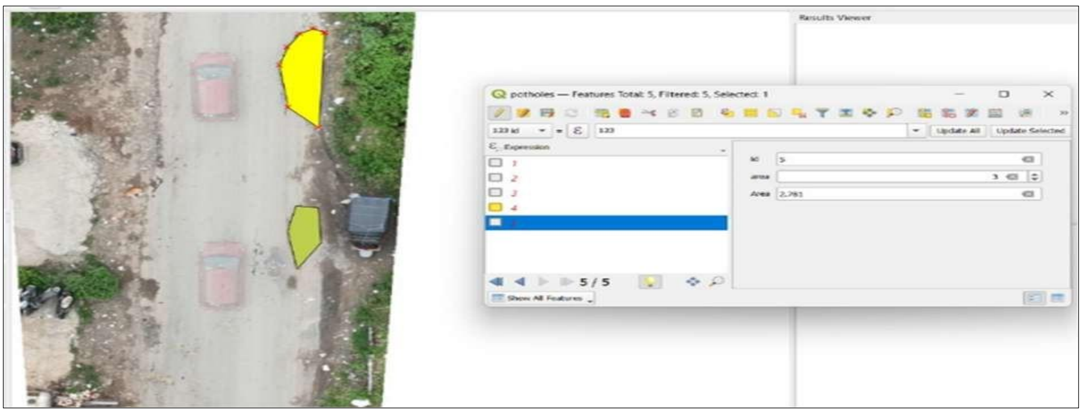

Table 1: Pothole Quantification

Pothole Area Attribute table extracted from QGIS (v3.34.15)								
Road - 01					Road - 02 & 03			
Pothol e id	Area from QGIS (Sq.m)	Assume Average Depth 0.05m IRC 81:1997	Quantity (Cu.m)		Pothol e id	Area from QGIS (Sq.m)	Assume Average Depth 0.05m IRC 81:1997	Quantit y (Cu.m)
1	1.611	0.05	0.08055		1	60.89	0.05	3.04
2	2.873	0.05	0.14365		2	4.911	0.05	0.25
3	7.112	0.05	0.3556		3	17.856	0.05	0.89
4	1.474	0.05	0.0737		4	20.629	0.05	1.03
5	10.601	0.05	0.53005		5	4.686	0.05	0.23

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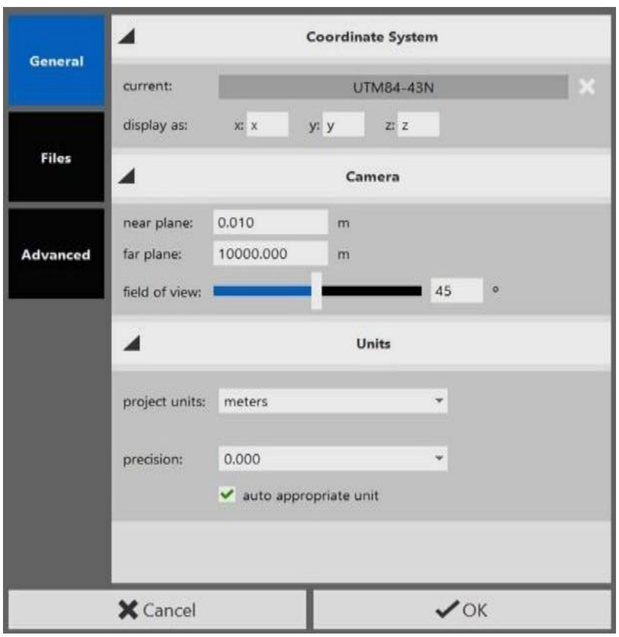
6	1.04	0.05	0.052		6	15.666	0.05	0.78
7	50.813	0.05	2.54065		8	0.158	0.05	0.01
8	0.3	0.05	0.015		9	0.161	0.05	0.01
9	0.402	0.05	0.0201		10	0.369	0.05	0.02
10	1.147	0.05	0.05735		11	2.834	0.05	0.14
11	9.916	0.05	0.4958		12	4.942	0.05	0.25
12	0.405	0.05	0.02025		13	6.742	0.05	0.34
13	19.922	0.05	0.9961		14	39.589	0.05	1.98
14	0.574	0.05	0.0287		15	0.125	0.05	0.01
15	3.062	0.05	0.1531		16	0.128	0.05	0.01
16	0.722	0.05	0.0361		17	0.555	0.05	0.03
17	0.267	0.05	0.01335		18	1.895	0.05	0.09
18	4.114	0.05	0.2057		19	0.937	0.05	0.05
19	6.895	0.05	0.34475		20	3.12	0.05	0.16
20	6.555	0.05	0.32775		21	0.714	0.05	0.04
21	28.904	0.05	1.4452		22	0.255	0.05	0.01
22	1.138	0.05	0.0569		23	45.967	0.05	2.30
23	0.294	0.05	0.0147		24	36.672	0.05	1.83
24	0.516	0.05	0.0258		25	9.639	0.05	0.48
25	0.459	0.05	0.02295		26	34.863	0.05	1.74
26	1.688	0.05	0.0844		27	20.007	0.05	1.00
27	2.826	0.05	0.1413		28	12.221	0.05	0.61
	165.63		**8.28**			**346.531**		**17.33**

Figure 6: Co-ordinate System in Recap Pro 2024



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4.3 Using the point cloud to create the digital twin model

4.3.1 Using autodesk recap pro 2024 to import point cloud

- Import Point Cloud: Import the .las file into Autodesk Recap 2024 to create a 3D road model.
- Set Coordinate System: Set UTM84-43N CRS for accurate analysis and alignment.
- Remove Noise: Eliminate inaccurate data to improve model accuracy and quality.
- Export Refined Data: Export cleaned data in .rcs format for use in Revit and Civil 3D.

4.3.2 Setting up point cloud in the autodesk recap pro 2024

Maintain spatial accuracy, Autodesk Civil 3D was configured as follows:

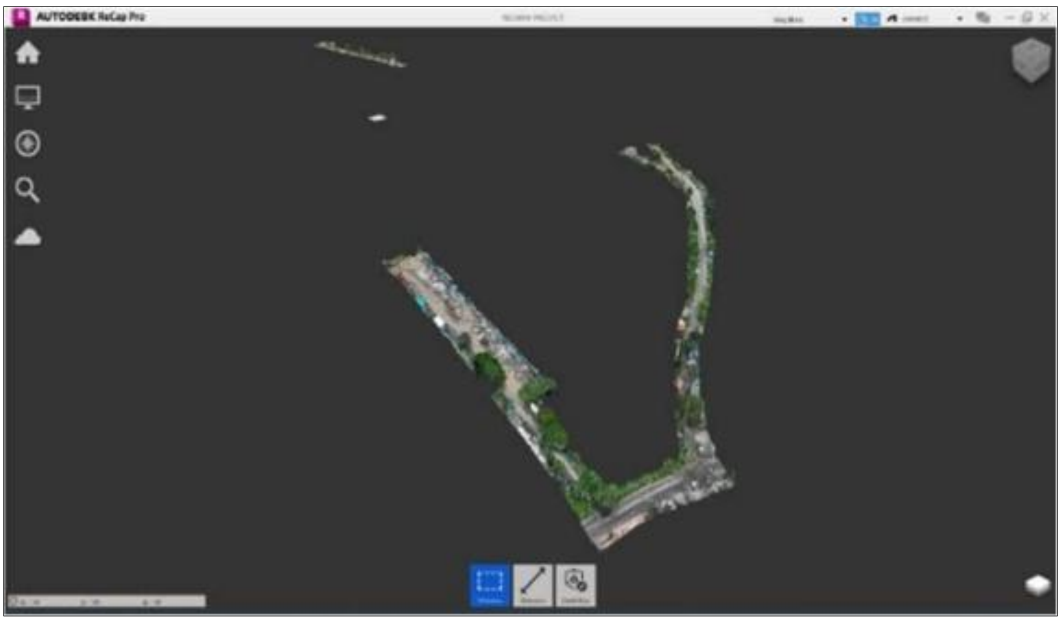
- The coordinate system was set to UTM84-43N, ensuring consistency with the processed point cloud.
- Geo Location and Aerial Mode settings were enabled to provide a real-world spatial reference for the imported data.

4.3.3 Importing and generating surface from point cloud

The cleaned .rcs point cloud "15-12-24" data were imported into Civil 3D for surface generation. The process included:

- Using the "Create Surface from Point Cloud" command to generate a terrain model.

Figure 7: Point Cloud in Recap Pro 2024



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- Selecting the existing grid choice and enabling the "Display Contour" feature to enhance surface visualization.
- Choosing the "No Filter" choice to include all available data points for correct surface modelling.

Figure 8: Point Cloud in Recap Pro 2024

Figure 9: Drawing Setup in Civil 3D 2024

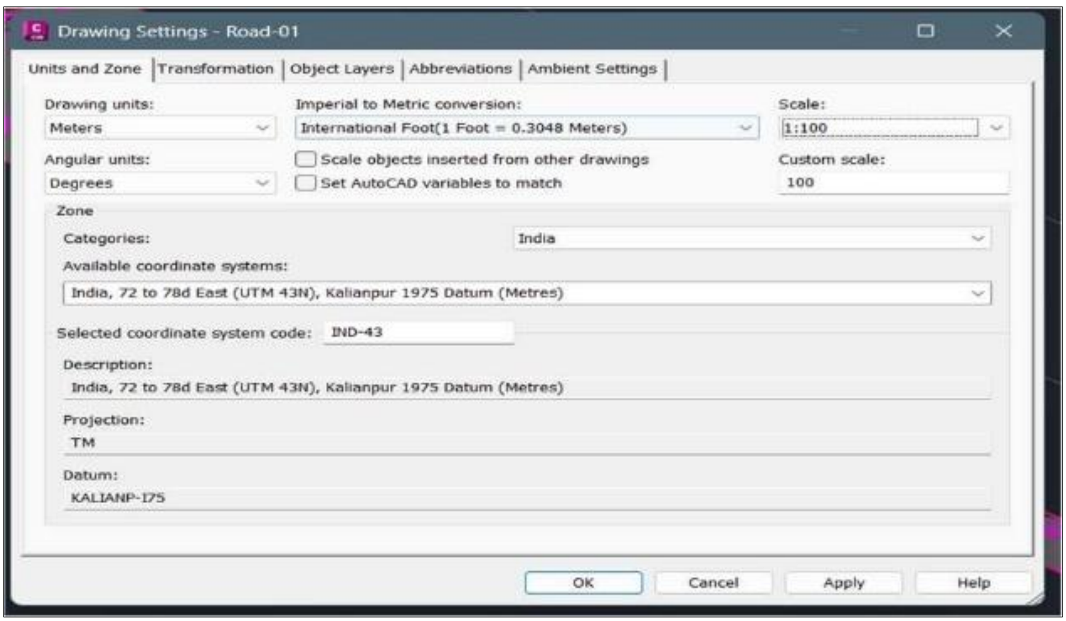

Figure 10: Coordinates System Setting in Civil 3D 2024

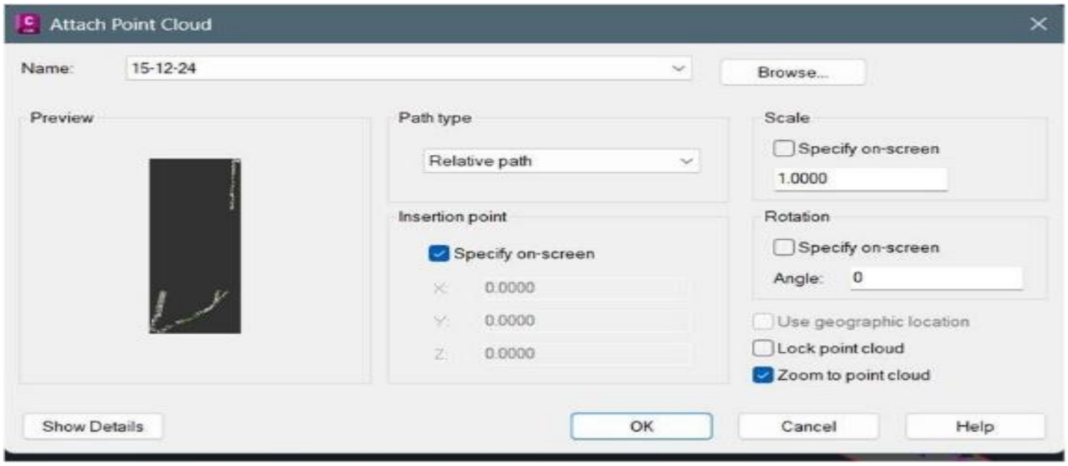

Figure 11: Enabling Real time Geolocation Setting in Civil 3D 2024

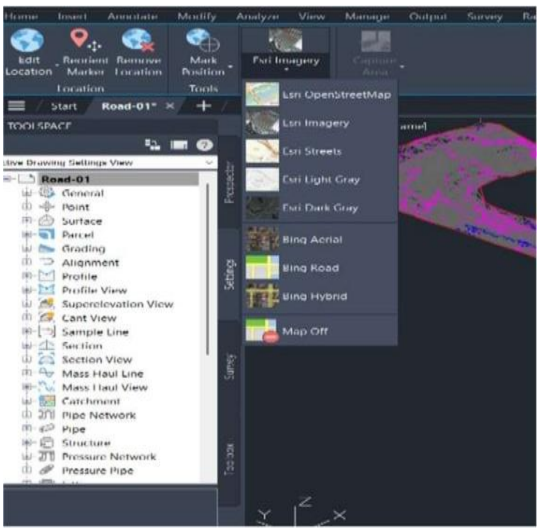

Figure 12: Enabling Real time Geolocation Setting in Civil 3D 2024

4.3.4 Editing and cleaning the surface

Refine the generated terrain model, the following modifications were applied:

- The Edit Style menu was accessed to create a TIN (Triangulated Irregular Network) Model from the imported point cloud.
- The model was further refined by cleaning and removing unnecessary lines to set up an exact boundary.
- Object viewer used to get real features after setting High Level of Details mode on.

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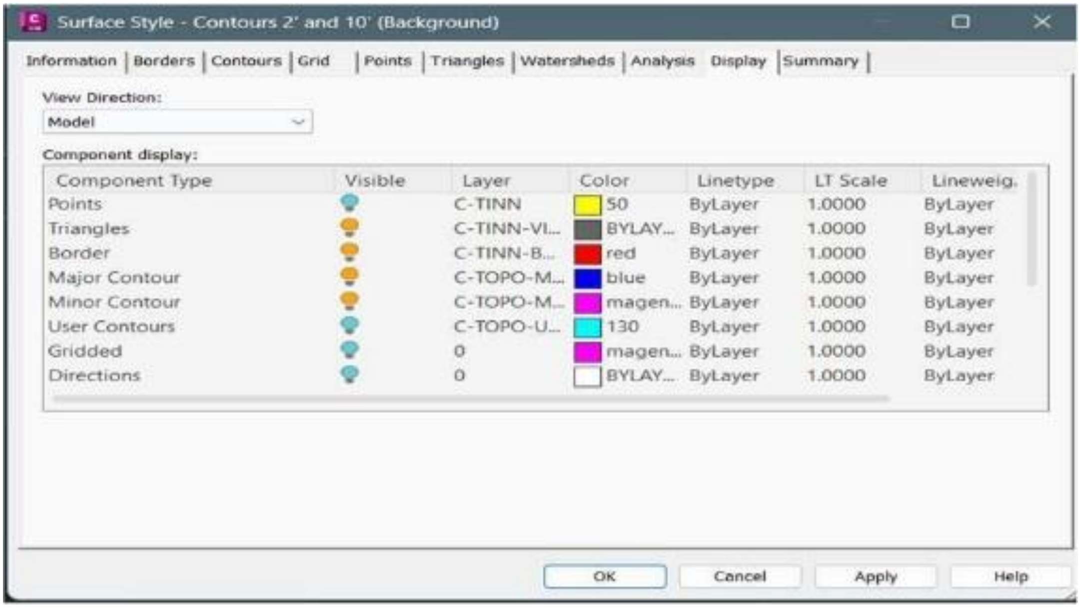
4.3.5 Exporting to a digital surface model (DSM)

The ultimate step involved exporting the refined terrain model:

- The cleaned TIN Model was converted into a Digital Surface Model (DSM).
- The DSM was saved for further analysis and integration into geospatial applications.

Figure 13: Legends for Digital Surface Model in Civil 3D 2024



4.4 Sustainable repair solution

Stone Matrix Asphalt (SMA) is highly recommended for pothole repairs due to its durability, resistance to wear and rutting, and suitability for heavy-traffic areas. According to MoRTH Clause 507, SMA's gap-graded composite combined with a modified bitumen binder makes it an effective choice for long-term pavement preservation. Its strong resistance to deformation and stability makes it ideal for regions with frequent potholes, reducing the need for constant maintenance and improving environmental road quality. As a polymer-modified asphalt, SMA enhances road lifespan while lowering maintenance costs, providing a sustainable solution for deteriorating roads.

4.4.1 Material requirements (MoRTH 5th revision clause 507.2)

SMA requires well-graded, durable coarse aggregates that improve the asphalt mix's structural strength and overall performance. A modified bitumen binder is essential, as it enhances resistance to temperature changes and stress from traffic loads. This improved binder boosts the mix's ability to resist cracking, rutting, and deformation, ensuring a longer-lasting

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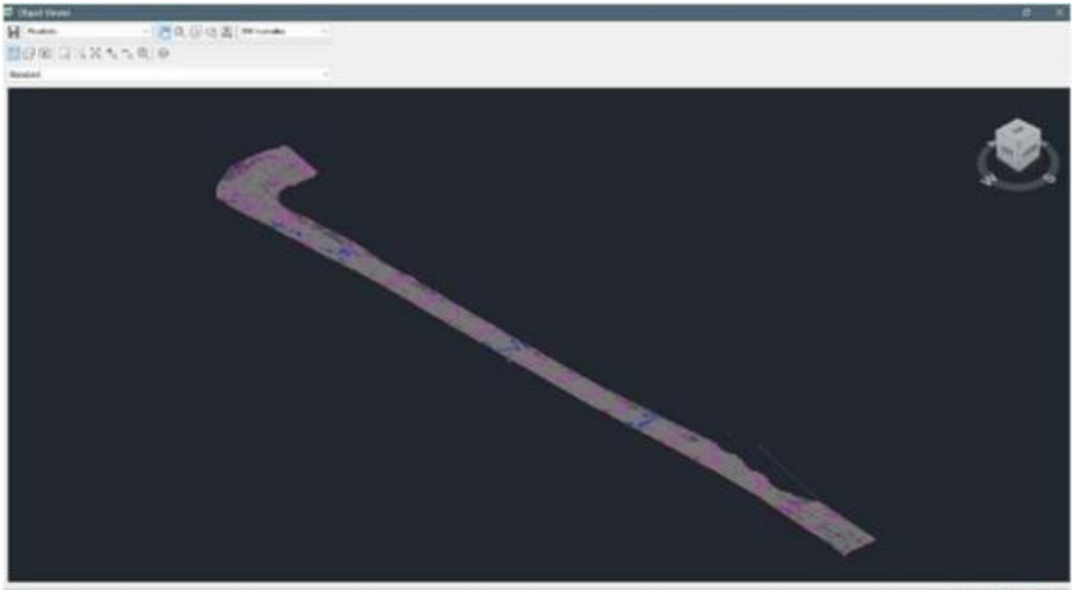
road surface. According to MoRTH Clause 507.2, careful selection of both bitumen binder and aggregates is crucial to achieving effective and durable pothole repairs.

Figure 14: Digital Surface Model in Civil 3D



4.4.2 Preparation and design of the mix (MoRTH 5th revision clauses 507.3 & 507.4)

A carefully designed SMA mix relies on precise aggregate gradation, binder content, and modifiers to enhance durability and rutting resistance. Maintaining proper gaps in the mineral aggregate (VMA) is crucial for ensuring long-term mix stability.

- Aggregate Gradation: Aggregates should be well graded, so they aid in compaction and reduction of the air voids.
- Binder Content: Bitumen content in the mix should be customized for eliminating.
- Binder Modifiers: This is known as binder modification - the use of the proper modifier to increase the binder's evergreen properties against environmental factors and aging.

4.4.3 Application process (MoRTH 5th revision clauses 507.5 & 507.6)

- Cleaning and Preparation: Remove dust, debris, and loose material from the pothole area to ensure proper bonding.
- Placement of SMA Mix: Apply the SMA mixture using standard hot-mix asphalt methods to level it with the road surface.
- Roller Compaction: Compact the repair area immediately with a roller to achieve the desired strength and durability.

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4.4.4 Compaction and finishing (MoRTH 5th revision clause 507.7)

Compaction is key for effective SMA-based pothole repairs, requiring minimal air spaces and uniform density after mixing for long-lasting performance.

- Uniform Density: Consistent density ensures the repair remains strong and durable.
- Minimized Air Voids: Lower air voids improve mix stability and reduce traffic-related damage.
- Structural Strength: Proper compaction enhances strength, allowing repairs to withstand heavy traffic.

4.4.5 Quality Control (MoRTH 5th Revision Clause 507.8):

Quality Control ensures high performance and longevity in SMA pothole repairs.

- Stability Testing: Confirms the mix can handle temperature changes and traffic stress.
- Binder Content: Ensures binder levels meet required specifications.
- Aggregate Gradation: Verifies proper grading for a stable mix.
- Mix Performance: Tests mix response to wear, rutting, and fractures.

As per MoRTH Clause 507.8, at least three samples per 500 tonnes of SMA must meet durability and design standards to ensure quality consistency.

4.5 Estimating the cost of the suggested pothole repair technique

Table 2: Digital Tools and Drone Survey Operating Costs for Pothole Detection

Operating Costs for Pothole Detection using Drone Survey and Digital Tools			
Sr. No	**Particular**	**Per day for 1.5**	**Reference**
1	Drone Flight Cost	50,000	Yelloskye
2	Autodesk Recap	93	Autodesk.in
3	AutoCAD	450	Autodesk.in
4	Autodesk Civil 3D	700	Autodesk.in
5	Processing Engineer	833	Autodesk.in
Total Operating Cost (INR)		**52,076**	

Table 3: Rate Analysis for Stone Matrix Asphalt Mix Production and Application

Rate Analysis for Stone Matrix Asphalt Mix Production and Application							
Sr.No.	**Item Description**	**Unit**	**Quantity**	**Rate**	**Amount (INR)**	**Total Amount (INR)**	**Remarks**
1	**Materials**						
1	VG-30	MT	22.5	42000	945,000		MH-SSR- 23
2	Cellulose fibre	MT	1.3	83000	109,560		
3	Coarse Aggregate	Cuft	7091.3	42	297,833.76		
4	Fine Aggregate	Cuft	2720.1	42	114,243.696		
5	Mineral Fillers	Cuft	211.7	42	8,890.56		

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2	**Labours**						
1	Beldar	Nos	5	650	3,250		MH-SSR-23
2	Mate	Nos	1	1,000	1,000		
3	**Plant & Machinery**						
1	HMP @60-90 TPH	Hrs	6	13,450	80,700		MH-SSR- 23
2	Paver Finisher	Hrs	7	3,500	24,500		
3	Smooth wheel roller	Hrs	4	600	2400		
4	Vibratory roller	Hrs	4	800	3200		
5	Tandon roller	Hrs	4	1350	5400		
6	Generator 250 KV	Hrs	6	2270	13620		
7	Dumper 15 MT	Day	1	5000	5000		
						16,14,598	
4	**Add 1% water charges**					16,146	
						16,30,744	
5	**Add 15% CPOH**					2,44,611.60	
						18,75,355.60	
6	**Unit Cost**					**4,167.46**	
7	**GST (18%)**					**4,918**	
Final Cost per Unit Tonne						**₹4,918**	

Table 4: Repair Cost using Stone Matrix Asphalt

Sr.no	**Particular**			**Cost Calculations**		**Reference**
A	Repair	Material	Calculations			
1	Repair (Cum)	Material	Required	For Stretch 1 + Stretch 2 8.28 + 17.33 25.61		QGIS Quantification Data
2	Consider 10% wastage			2.561		Assumption
3	Total Repair Material Required (Cum)			28.171		
4	SMA Required of Density 2.5 MT/Cum			Total Repair Required (Cum) X SMA (MT/Cum)	Material Density	
				70.43		
5	SMA Required (Tonnes)			70.43		
B	Total Repair Cost					
1	SMA Cost (Production + Application + Transportation)			4,918.00		
2	**Total SMA Cost (INR)**			**3,46,362.45**		

Table 5: Total Cost Pothole Repair

Total Cost Pothole Repair (Drone Survey, QGIS, Digital Twin, and Stone Matrix Asphalt)			
Sr.no	**Particular**	**Cost (INR)**	**Reference**
1	Operating Cost for Pothole Detection using Drone Survey, QGIS and Digital Twin Technology	52,076	
2	Repair Cost using Stone Matrix Asphalt	3,46,362.50	
Total Cost (INR)		**3,98,438.5**	

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Table 6: Costing of Current Pothole Repair Methodology

<table>
<tr><th colspan="9">Costing of Current Pothole Repair Methodology (Hot Mix Asphalt)</th></tr>
<tr><th>Sr.no</th><th colspan="4">Particular</th><th colspan="3">Cost Calculations</th><th>Reference</th></tr>
<tr><th colspan="9">Pothole Detection Cost using Total station Profile Surveying</th></tr>
<tr><td rowspan="2">A</td><td colspan="4">Road Survey Cost for per KM (INR)</td><td colspan="3">46,615.00</td><td rowspan="2">Item-no.40 SSR-23-24 | - | MH</td></tr>
<tr><td colspan="4">For 1.5 KM</td><td colspan="3">69,922.50</td></tr>
<tr><th colspan="9">Repair Cost using Hot Mix Asphalt VG-30</th></tr>
<tr><td rowspan="3">1</td><td rowspan="3">Repair (Cum)</td><td rowspan="3"></td><td rowspan="3">Material</td><td rowspan="3">Required</td><td>For Stretch Stretch 2</td><td>1</td><td>+</td><td rowspan="3">QGIS Quantification Data</td></tr>
<tr><td colspan="3">8.28 + 17.33</td></tr>
<tr><td colspan="3">25.61</td></tr>
<tr><td>2</td><td colspan="4">Consider 10% wastage</td><td colspan="3">2.561</td><td>Assumption</td></tr>
<tr><td>3</td><td>Total (Cum)</td><td>Repair</td><td>Material</td><td>Required</td><td colspan="3">28.171</td><td></td></tr>
<tr><td rowspan="2">4</td><td colspan="4" rowspan="2">Hot Mix Asphalt Required of Density 2.5 MT/Cum</td><td colspan="3">Total Repair Material Required (Cum) X SMA Density (MT/Cum)</td><td></td></tr>
<tr><td colspan="3">70.43</td><td></td></tr>
<tr><td>5</td><td colspan="4">HMA Required (Tonnes)</td><td colspan="3">70.43</td><td></td></tr>
<tr><td>A</td><td colspan="7">Total Repair Cost</td><td></td></tr>
<tr><td>1</td><td colspan="4">SMA Cost (Production + Application + Transportation)</td><td colspan="3">6100.00</td><td>From PMC Hot Mix Plant</td></tr>
<tr><td>2</td><td colspan="4">Total HMA Cost</td><td colspan="3">4,29,607.75</td><td></td></tr>
<tr><th colspan="9">Total Cost of Pothole Repair</th></tr>
<tr><td>A</td><td colspan="4">Pothole Detection Cost using Total station Profile Surveying</td><td colspan="4">69,922.50</td></tr>
<tr><td>B</td><td colspan="4">Repair Cost using Hot Mix Asphalt VG-30</td><td colspan="4">4,29,607.75</td></tr>
<tr><td colspan="5">Total Cost (INR)</td><td colspan="4">4,99,530</td></tr>
</table>

5.0 Results

Drone surveys provide fast and accurate pothole detection (90%–95%), though total station surveys offer higher accuracy (98%–99%) but are slower and more expensive. QGIS with UTM84-43N georeferencing ensures precise pothole measurement (95%–99%), aiding targeted repair planning. Digital Twin models enhance road maintenance by predicting damage patterns and improving repair strategies.

Stone Matrix Asphalt (SMA) outperforms Hot Mix Asphalt (HMA) in durability and rutting resistance, making it ideal for high-traffic roads. Drone surveys save ₹17,846.50 (25.53%) over total station surveys, while SMA repairs save ₹83,245.25 (19.38%) over HMA, offering a cost- effective and sustainable solution for long-term road maintenance.

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Figure 15: Pothole Detection Cost Comparison

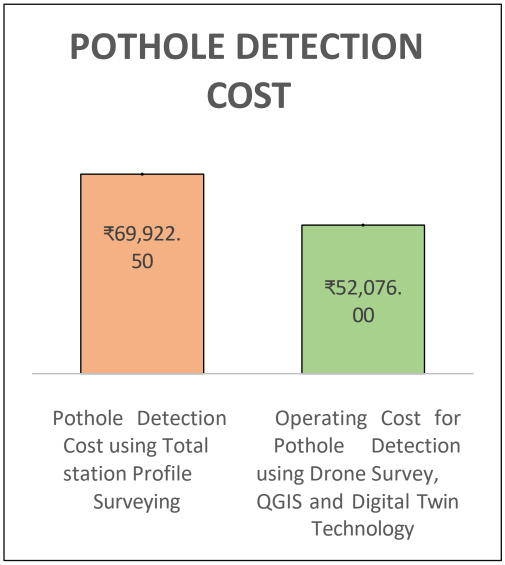
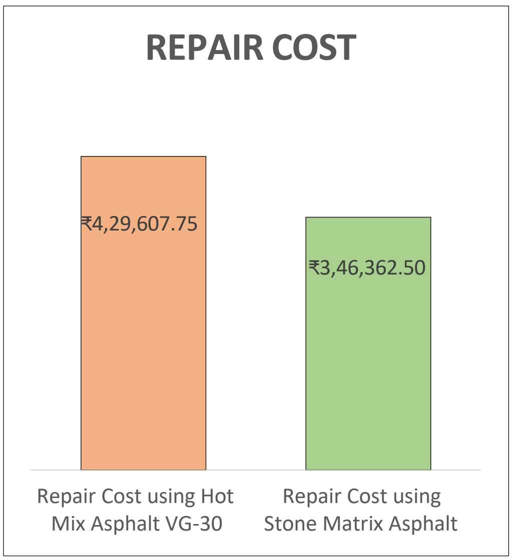


Figure 16: Repair Cost Comparison



6.0 Limitations and Challenges

- High Costs: Equipment, software, and training are expensive.
- Technical Complexity: Requires advanced skills and high computing power.

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- Weather Impact: Rain, fog, and wind affect drone performance.
- System Compatibility: Issues with legacy system integration.

7.0 Future Trends

- AI for Pothole Detection: AI predicts road damage and maintenance needs.
- Smart Roads with IoT: IoT sensors monitor road stress and damage.
- Cloud-Based Platforms: Real-time data sharing improves project management.
- Eco-Friendly Materials: Use of recycled and biodegradable binders.
- Life Cycle Assessment: Promotes sustainable road design and repair.

8.0 Conclusion

Drone surveys, QGIS, Digital Twin models, and Stone Matrix Asphalt (SMA) have improved pothole detection and repair by increasing accuracy and cutting costs. Drone surveys combined with QGIS and Digital Twin models provide 90%–95% accuracy and reduce survey costs by 25.53%. SMA repairs are 19.38% more cost-effective than Hot Mix Asphalt (HMA) due to better durability, making them ideal for high-traffic roads. However, high initial costs and technical complexity make adoption difficult for smaller municipalities. Weather conditions can also disrupt drone operations and affect data accuracy. Future innovations like AI-driven pothole detection, smart roads with IoT sensors, and cloud-based data sharing will further improve road maintenance and reduce costs.

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