International Journal of Advances in Applied Sciences (IJAAS)
Vol. 14, No. 2, June 2025, pp. 345~351
ISSN: 2252-8814, DOI: 10.11591/ijaas.v14.i2.pp345-351

Road pavement deformation using remote sensing technique

Kishan Patel, Rajesh Gujar
Department of Civil Engineering, Pandit Deendayal Energy University, Gandhinagar, India

Article Info

Article history:

Received Apr 14, 2024
Revised Mar 5, 2025
Accepted Mar 28, 2025

Keywords:

Deformation
Potholes
Remote sensing
Road pavement
Synthetic aperture radar

ABSTRACT

The road surface reflects the status of the city's infrastructure. Road safety and driving comfort can be affected by the rough surface. To minimize road hazards, pavement conditions must be periodically inspected for damaged surfaces. A quick and efficient data collection can be provided by the radar images. For a large spatial coverage, radar image provides a non-destructive data collection technique for analyzing road conditions and classifying distress. The surface distress can be correlated by analyzing the images collected from high-resolution cameras and satellites. This article outlines the applicability of synthetic aperture radar (SAR) and interferometric synthetic aperture radar (InSAR) based images to manage and monitor pavement infrastructure. Therefore, the detection of deteriorating surfaces can be improved by analyzing the radar images timely. The results showed the deficiencies on the surface that can be used to mitigate bad pavement conditions and allow road users to use good road infrastructure with safety and comfort.

This is an open access article under the CC BY-SA license.

Corresponding Author:

Rajesh Gujar
Department of Civil Engineering, Pandit Deendayal Energy University
Knowledge Corridor, Raisan Village, PDPU Road, Gandhinagar, Gujarat 382007, India
Email: rajesh.gujar@sot.pdpu.ac.in

1. INTRODUCTION

Road infrastructures are an important asset for any country as they serve connectivity for the transportation of goods and humans. An inefficient road network can cause obstacles for humans in communications for commerce and activities. Therefore, it is necessary to maintain road infrastructure timely and effective. Continuous wear and tear of road surfaces cause damage and produce deficiencies. When the road surface counteracts the axel loads of 4th power, it deteriorates more quickly [1]. Initially, different kinds of cracks are formed and converted into potholes if not addressed when the severity is moderate. Thus, monitoring road conditions has become more critical as repairing the potholes costs more than renewing the cracks. The well-maintained surface condition provides an enjoyable experience to its users. The improvement of the transport system in terms of driving safety and comfort can be done by continuous monitoring of road surfaces. Frequent data collection and timely detection of deficiencies are two major obstacles in surface monitoring. The former becomes more challenging when it comes to manual inspection. It consists of data collection by doing manual site inspections and drawing road networks manually. This method also encounters a high workload and low efficiencies [2], [3]. Therefore, automatic data collection methods have become more effective in recent decades. This method emphasizes more features such as line detection, surface classification, and mathematical morphology [4]–[6]. Many studies and experts of highway engineering agencies have explained that the timely detection of surface deformation can be helpful for taking preventive measures to ensure savings in maintenance costs, enhance life, and preserve quality and safety [7]. Urban road networks encounter a larger population. Therefore, it requires more advanced tools for data collection, analysis, planning, and monitoring of road surfaces. Typically, the cost of preserving a frequently maintained road is maybe less than three times of deteriorated road which occurred due to lack of timely maintenance [8]. Remote sensing techniques are useful in data collection from anywhere and anytime. Many researchers used optical images to detect road surface deficiencies in which the surfaces may appear as dark and bright surfaces [9]. Whereas, these surfaces act differently in radar images which are based on microwave wavelengths and their backscattering responses. This study focuses on the techniques and processing of images from radar. It provides remote detection, identifying, classifying, and analyzing pavement distress.

There have been many studies carried out with synthetic aperture radar (SAR) technology for significant monitoring of road pavement surfaces in past decades [10]. One of the advantages of SAR images is that it helps to sense large geographical areas. These data sets can be utilized for a wide range of, such as from the earth sciences to military reconnaissance. Although these data may cover broad regional or continental regions in a single image, data collection, quality, and use might be restricted by revisit durations, atmospheric interferences, and spatial resolution [11]. These spatial dataset helps to analyze the road surface features. This study focuses on the use of multiple SAR images for a significant study area for different durations. This enables in identification of changes in road surface distress and their severity with respect to time. Also, the accuracy of classification is considered due to the impact of spatial resolution, in studies [12]–[15] considered the optimum spatial resolution before classification. [14] computed that the resolution capacity was related to the accuracy of the classification.

This research aims to provide a technique to extract road networks accurately while maintaining their integrity from SAR images. Also aims to analyze the distress values computed from the amplitude of the SAR images. Our research offers fresh insights into integrating multiple sources of SAR and digital data for the challenging task of road extraction. Given the complexity of road extraction, our study proposes novel ideas for combining SAR, optical, and digital data to improve the process. However, the limited coverage area in optical images may reduce the exposure of the study area. This can be improved by using optical data with a large coverage area. The use of radar images in transportation research is a growing and economically beneficial area of study. Crack detection by combining various analysis algorithms using ultra-sonic sensors with imaging techniques was done. The study revealed individual cracks detected with thickness greater than 0.1 mm, with a maximum error in length of 7.3%.

The introduction is followed by the research method, which focuses on the study area, data acquisition, data analysis pre-processing of SAR images. This section also describes how road extraction is done accurately. In section 3, experiments on road extraction and road distress are presented and the results are evaluated. Finally, conclusions were drawn from the deformation values and results evaluated.

2. RESEARCH METHOD

SAR image is a complex image that contains geographical features. It requires the detection of road surface only amongst other geographical features such as water bodies, open land, vegetation cover, and buildings. Mathematical morphology can be used in road characteristics to ensure line linkages and to smooth the road edges [16]. The proposed method usually considers several aspects such as study area, processing flow, resolution type and size, and human intervention [17], [18].

2.1. Study area

Various road surfaces with different distress are required to carry out this research. For this, three different road networks of Ahmedabad City (Gujarat, India) were selected for the research with different geometric features. Figure 1 shows the Google Earth images of all three road networks with blue color outlines. The first study area is Gota-Ognaj Road shown in Figure 1(a). The second road network selected is Science-City Road and the third study area chosen is Priyakant Parikh Marg as shown in Figure 1(b) and Figure 1(c) respectively. All three road networks pass through the residential and commercial buildings.

2.2. Data collection

Majorly three types of images called datasets were collected namely SAR images, optical images, and digital images. In this study, SAR images provided by the European Agency (ESA) Copernicus Open Access Hub of Sentinel-1A product were acquired. There are a total 12 number of images from September 2023 to February 2024 were acquired. Whereas for optical images, Landsat-9 images by USGS Earth Explorer were accessed. High-resolution digital camera used for capturing digital images.

2.3. Data analysis

The SAR image is created by transmitted and received microwaves from illuminated geographical features. Each pixel of the SAR image has amplitude as well as phase. Due to amplitude, the radiation of microwave backscatter from each pixel's object provides differentiation of surface characteristics. The amplitude is more dependent on the ability of the surface to reflect away the radiation and its roughness [19]. Image processing is the first step towards data analysis. SAR image is first required to be calibrated. Then after, a single-looking SAR image must be converted to multilooking to get maximum road surface features. After that, various image processing should be done, such as speckle filtering and backscattering that help to remove dominant multiplicative [20] and additive noise present in SAR images, respectively. The former noise was minimized by a Refined-Lee speckle filter with a 3×3 window [21]. Figure 2 shows the step-by-step procedure of SAR image processing.

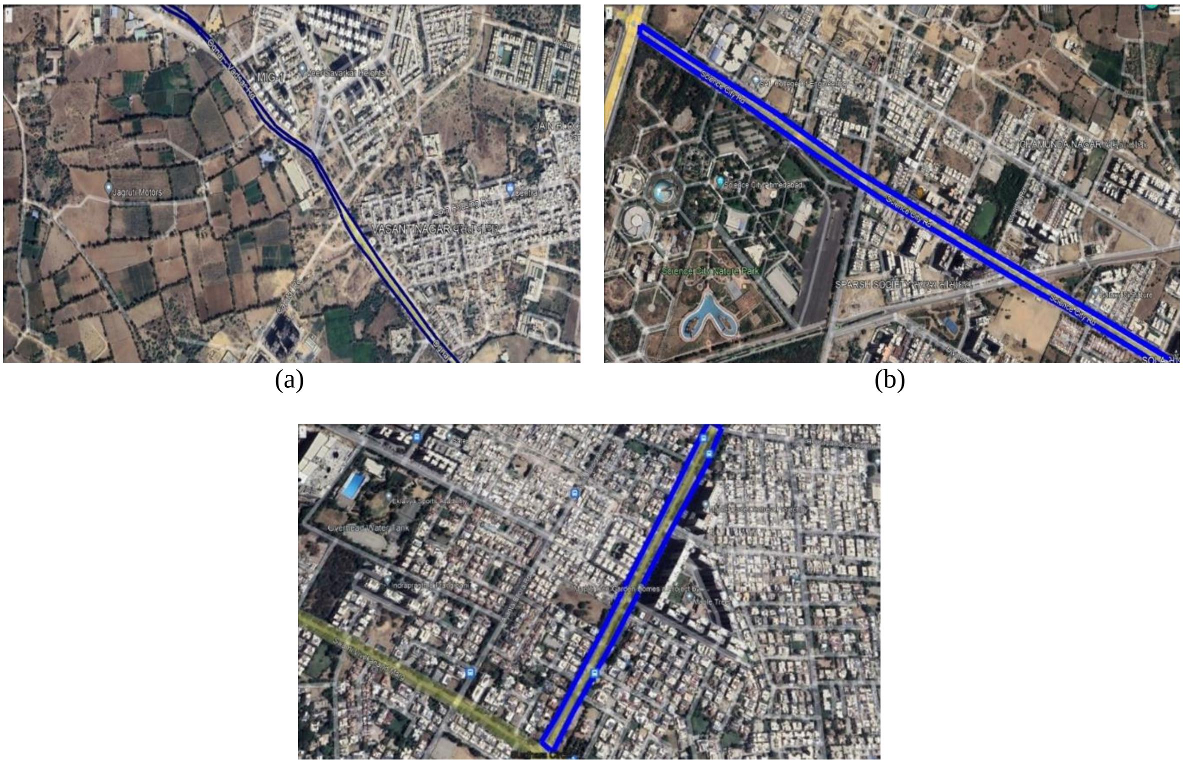

Figure 1. The study area of the road network selected for Ahmedabad City of (a) Gota-Ognaj Road, (b) Science City Road, and (c) Priyakant Parikh Marg

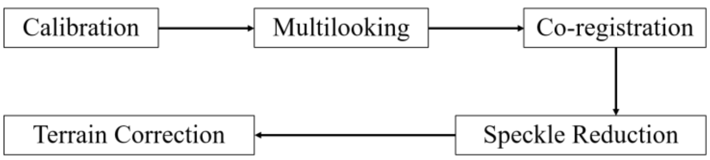

Figure 2. Data processing steps for SAR imagery

When the image is converted to a multilook complex (MLC), it reduces the spatial resolution and enhances the spatial resolution. Whereas pixel value solely shows the radar backscatter of the reflecting surface. Images with the same acquisition mode and orbit placed due to co-registration simultaneously. Applying a speckle filter helps to reduce and/or remove blurred surfaces and features. A digital elevation model (DEM) is used to correct SAR geometric distortion by geocoding the image for terrain correction. Typically, there are three types of terrain correction that give better results namely, sigma-naught (σo), beta-naught, and gamma-naught. Out of them, sigma naught gives better-calibrated radar brightness measurements [22]. Each pixel's σo values are estimated individually, without any spatial averaging. The estimated noise-equivalent beta-naught (NEBN) values are then subtracted from the σo values to reduce additive noise [23]. The σo image with reduced noise helps in comparing backscatter measurements on different surfaces and allows for the estimation of surface properties like roughness. Following that, the application of multilooking in the spatial domain aims to decrease speckle and improve the signal-to-noise ratio by averaging adjacent pixels in both the range and azimuth directions [24]. SAR images show indefinite lines for the road network. This happens due to the relatively smooth surface of roads than surroundings, hence providing a mirror-like reflection resulting in low returns of a radar signal. With more geometric features, this effect multiplies. As a result, roadways appear as bright lines due to multiple bounces in the azimuth direction as other configurations like elevated roads, road rails, road borders, and bridges exist. Since radars are side-looking sensors, the direction of looking greatly influences the geographic features of the acquired image [25]. Different polarization states based on transmitted-received electromagnetic signals give different results post-processing the image. It has polarization of horizontal and vertical and a combination of both as well. The horizontal polarization has images with electromagnetic signals both transmitted and received horizontally (HH) while signals transmitted horizontally and received vertically (HV). In contrast, vertical polarization has images with electromagnetic signals both transmitted and received vertically (VV) while signals transmitted vertically and received horizontally (VH). Any polarization can give optimum results for any road network. Dual-polarization and quad-polarization if we combine any two and all four, respectively. The scattering matrix can be converted into other polarization bases after it has been acquired, such as the circular polarization base, allowing the same polarimetric data to be read from several angles [10]. An algorithm was developed after processing all images for automatic real-time distress detection on the surface. Figure 3 shows a road network of Ahmedabad City extracted from the SAR image.

Figure 3. The road network of Ahmedabad City

3. RESULTS AND DISCUSSION

This study looked into the synergic use of interferometric SAR (InSAR) and digital to get more accurate results while previous studies such as [26] used the fusion of optical, SAR, and light detection and ranging (LiDAR) and [27] used the combination of optical and polarimetric SAR (PolSAR). Their results showed improvement in road segmentation methods and did not explicitly address its influence on surface deficiencies. Therefore, this paper aims to provide quick and accurate data assessment by using SAR images to analyze the road surface deformation. It also explores the requirement for an effective and automated pavement health monitoring system in the transportation industry. After analyzing the thousands of pixel values of $\sigma 0_{VV}$ and $\sigma 0_{VH}$, the surface deformation was obtained. Out of these values, ten values are shown in Table 1.

Table 1. The pixel value of Science City Road

Sr. No.	$\sigma 0_{VH}$	$\sigma 0_{VV}$	Amplitude VH
1	0.023525	0.181795	523.420579
2	0.025458	0.175113	306.649855
3	0.034337	0.247856	286.445047
4	0.031274	0.252146	256.729305
5	0.038459	0.279860	246.712207
6	0.028796	0.273875	243.685022
7	0.029312	0.252015	226.939401
8	0.024292	0.228905	190.175340
9	0.043151	0.440228	173.660436
10	0.018639	0.140595	150.668089

These values are converted with mathematical modeling into measurable quantities, say lengths. Therefore, lengths of road deficiencies can be identified. These values are compared to manually calculated values as well as digital images captured for those road network deficiencies.

It can be seen from Figure 4 that the surface distress detected can be verified with the actual digital image. This can be done with the geo location of that specific distress. The manual value of distress is then compared to the value of the SAR image. It gives an equivalent value with an error of 8 mm. The possible reason for this is due to taking the mean value of each pixel. In various cases due to other road features, volume backscatter arises. However, a better resolution of the SAR image will give results with higher accuracy as it provides more pixels and values in a single image. Future research may not require the optical and digital datasets used in this study as the higher spatial resolution will give enough information on surface deformation with improved results and eventually save time.

Figure 4. Roadway deformation on Science City Road

4. CONCLUSION

This research aims to utilize SAR images to detect and identify road surface deformations. It can be obtained by assessing the road surface from the radar image and converting the pixel values into measurable quantities. Thus, the exact location of the surface deformations can be identified accurately. This method can be used to determine and analyze the degree of deficiencies at the early stage. Therefore, the maintenance and repair work of the road surface can be done well in advance to improve the experience of the road surface for its users. Machine learning (ML) can be applied to detect and classify the distress of road surfaces from SAR images, providing an alternative to data analysis of road information. In future work, we should use the proposed method for the classification of pavement distresses of large road networks to test the robustness and computational capability of our method.

FUNDING INFORMATION

The authors state no funding is involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Kishan Patel	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	
Rajesh Gujar	✓	✓		✓	✓			✓		✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

DATA AVAILABILITY

- The data that support the findings of this study are available on request from the corresponding author, [RG]. The data, which contain information that could compromise the privacy of research participants, are not publicly available due to certain restrictions.
- The data that support the findings of this study are available from the Copernicus Open Access Hub of Sentinel-1A product by the European Space Agency and USGS Earth Explorer. Restrictions apply to the availability of these data, which were used under license for this study. Data are available on https://browser.dataspace.copernicus.eu/ and https://earthexplorer.usgs.gov/ with the permission of the European Space Agency and USGS.

REFERENCES

[1] H. B. Ibrahim, M. Salah, F. Zarzoura, and M. El-Mewafi, "Smart monitoring of road pavement deformations from UAV images by using machine learning," *Innovative Infrastructure Solutions*, vol. 9, no. 1, p. 16, Jan. 2024, doi: 10.1007/s41062-023-01315-2.

[2] W. Wang, N. Yang, Y. Zhang, F. Wang, T. Cao, and P. Eklund, "A review of road extraction from remote sensing images," *Journal of Traffic and Transportation Engineering (English Edition)*, vol. 3, no. 3, pp. 271–282, Jun. 2016, doi: 10.1016/j.jtte.2016.05.005.

[3] H. R. R. Bakhtiari, A. Abdollahi, and H. Rezaeian, "Semi automatic road extraction from digital images," *The Egyptian Journal of Remote Sensing and Space Sciences*, vol. 20, no. 1, pp. 117–123, Jun. 2017, doi: 10.1016/j.ejrs.2017.03.001.

[4] I. Kahraman, I. R. Karas, and A. E. Akay, "Road extraction techniques from remote sensing images: a review," *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XLII-4/W9, pp. 339–342, Oct. 2018, doi: 10.5194/isprs-archives-XLII-4-W9-339-2018.

[5] P. Liu, Q. Wang, G. Yang, L. Li, and H. Zhang, "Survey of road extraction methods in remote sensing images based on deep learning," *PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, vol. 90, no. 2, pp. 135–159, Apr. 2022, doi: 10.1007/s41064-022-00194-z.

[6] D. Patil and S. Jadhav, "Road extraction techniques from remote sensing images: a review," in *Innovative Data Communication Technologies and Application*, Springer, Singapore, 2021, pp. 663–677, doi: 10.1007/978-981-15-9651-3_55.

[7] American Association of State Highway and Transportation Officials, *AASHTO guidelines for pavement management systems*. Washington D.C.: American Association of State Highway and Transportation Officials, 1990. [Online]. Available: https://books.google.co.id/books?id=TRT9GwAACAAJ

[8] American Association of State Highway and Transportation Officials (AASHTO) and Road Information Program, *Rough roads ahead: fix them now or pay for them later*. Washington D.C.: AASHTO, 2009.

[9] H. Zhang, H. Lin, Y. Li, Y. Zhang, and C. Fang, "Mapping urban impervious surface with dual-polarimetric SAR data: an improved method," *Landscape and Urban Planning*, vol. 151, pp. 55–63, Jul. 2016, doi: 10.1016/j.landurbplan.2016.03.009.

[10] K. Ouchi, "Recent trend and advance of synthetic aperture radar with selected topics," *Remote Sensing*, vol. 5, no. 2, pp. 716–807, Feb. 2013, doi: 10.3390/rs5020716.

[11] E. Schnebele, B. F. Tanyu, G. Cervone, and N. Waters, "Review of remote sensing methodologies for pavement management and assessment," *European Transport Research Review*, vol. 7, no. 2, Jun. 2015, doi: 10.1007/s12544-015-0156-6.

[12] R. Xu, H. Zhang, and H. Lin, "Urban impervious surfaces estimation from optical and SAR imagery: a comprehensive comparison," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 10, no. 9, pp. 4010–4021, Sep. 2017, doi: 10.1109/JSTARS.2017.2706747.

[13] C. E. Woodcock and A. H. Strahler, "The factor of scale in remote sensing," *Remote Sensing of Environment*, vol. 21, no. 3, pp. 311–332, Apr. 1987, doi: 10.1016/0034-4257(87)90015-0.

[14] D. J. Marceau, "The scale issue in the social and natural sciences," *Canadian Journal of Remote Sensing*, vol. 25, no. 4, pp. 347–356, Oct. 1999, doi: 10.1080/07038992.1999.10874734.

[15] J. Ju, S. Gopal, and E. D. Kolaczyk, "On the choice of spatial and categorical scale in remote sensing land cover classification," *Remote Sensing of Environment*, vol. 96, no. 1, pp. 62–77, May 2005, doi: 10.1016/j.rse.2005.01.016.

[16] R. Maurya, P. R. Gupta, and A. S. Shukla, "Road extraction using k-means clustering and morphological operations," in *2011 International Conference on Image Information Processing*, IEEE, Nov. 2011, pp. 1–6, doi: 10.1109/ICIIP.2011.6108839.

[17] J. Cheng, G. Gao, X. Ku, and J. Sun, "Review of road network extraction from SAR images," *Journal of Image and Graphics*, vol. 18, no. 1, pp. 11–23, 2013, doi: 10.11834/jig.20130102.

[18] J. H. Cheng, *Road extraction in high-resolution SAR images*. Changsha: National University of Defense Technology, pp. 1-132, 2013.

[19] A. Ferretti, A. Monti-Guarnieri, C. Prati, and F. Rocca, *InSAR principles: guidelines for SAR interferometry processing and interpretation*. ESA Publications, 2007.

[20] F. Argenti, A. Lapini, T. Bianchi, and L. Alparone, "A tutorial on speckle reduction in synthetic aperture radar images," *IEEE Geoscience and Remote Sensing Magazine*, vol. 1, no. 3, pp. 6–35, Sep. 2013, doi: 10.1109/MGRS.2013.2277512.

[21] A. S. Yommy, R. Liu, and A. S. Wu, "SAR image despeckling using refined Lee filter," in *2015 7th International Conference on Intelligent Human-Machine Systems and Cybernetics*, IEEE, Aug. 2015, pp. 260–265, doi: 10.1109/IHMSC.2015.236.

[22] Z. Meyer and P. Cichocki, "Analysis of combined pile raft foundations based on a static load test," *Civil Engineering and Architecture*, vol. 8, no. 2, pp. 101–112, Apr. 2020, doi: 10.13189/cea.2020.080208.

[23] Airbus Defence and Space I Geo-Intelligence, *Radiometric calibration of terrasar-x data: beta naught and sigma naught coefficient calculation*. Infoterra GmbH, 2014.

[24] A. Braun and L. Veci, *Sentinel-1 toolbox: sar basics tutorial*. Array Systems Computing Inc., 2021.

[25] A. Hendry, S. Quegan, and J. Wood, "The visibility of linear features in SAR images," in *International Geoscience and Remote Sensing Symposium, "Remote Sensing: Moving Toward the 21st Century".*, IEEE, pp. 1517–1520, doi: 10.1109/IGARSS.1988.569508.

[26] Y. Lin, H. Zhang, G. Li, T. Wang, L. Wan, and H. Lin, "Improving impervious surface extraction with shadow-based sparse representation from optical, SAR, and liDAR data," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 12, no. 7, pp. 2417–2428, Jul. 2019, doi: 10.1109/JSTARS.2019.2907744.
[27] H. Zhang, L. Wan, T. Wang, Y. Lin, H. Lin, and Z. Zheng, "Impervious surface estimation from optical and polarimetric SAR data using small-patched deep convolutional networks: a comparative study," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 12, no. 7, pp. 2374–2387, Jul. 2019, doi: 10.1109/JSTARS.2019.2915277.

BIOGRAPHIES OF AUTHORS

Kishan Patel is a research scholar in the Department of Civil Engineering at Pandit Deendayal Energy University, India. He holds an M. Tech degree in Infrastructure Engineering and Management specializing in Transportation Engineering. His research areas are pavement maintenance, defect detection, and pavement management systems. He has presented more than 5 research papers at various international conferences. He can be contacted at email: kishan.pphd19@sot.pdpu.ac.in.

Dr. Rajesh Gujar is currently an Associate Professor in the Department of Civil Engineering at the School of Technology, Pandit Deendayal Energy University. He holds a Ph.D. in Transportation Engineering from Sardar Vallabhbhai National Institute of Technology, Surat, earned in 2016. Additionally, he completed his M.E. in Construction Engineering and Management from B.V.M. Engineering College, S.P. University V.V. Nagar, Anand, in 1999, and his B.E. in Civil-Water Management from S.G.G.S.C.E. and T, Nanded (M.S), Dr. B. A. Marathwada University, Aurangabad (M.S.), in 1997. He has an extensive educational background and is affiliated with institutions such as S.V. National Institute of Technology, Surat, CEPT University, and Lamar University, Beaumont, Texas, USA. He has received recognition for his contributions, including being awarded the "Best Performance in Public Works Department in Akola Municipal Corporation, Akola (Maharashtra)." He has an impressive publication record with numerous articles, chapters, and conference papers. Notable publications include articles in prestigious journals such as "International Journal of Construction Management," "Journal of The Institution of Engineers (India): Series A," and "Materials Today Proceedings." His research spans various topics, including sustainable road maintenance, the application of machine learning techniques in transportation projects, and the utilization of alternative materials in construction. He has presented his work at conferences and has actively contributed to the academic community. He can be contacted at email: rajesh.gujar@sot.pdpu.ac.in.