İSTANBUL UNIVERSITY CERRAHPAŞA

ORIGINAL ARTICLE
Electrica 2024; 24(2): 503-514

Hazardous Zone Identification by Spectral Analysis of Ground Penetrating Radar Response

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Cite this article as: U. Joshi, R. Dev Garg, N. Sharma, V. Kumar Joshi and K. Sharma, "Hazardous zone identification by spectral analysis of ground penetrating radar response," *Electrica*, 24(2), 503-514, 2024.

ABSTRACT

Ground penetrating radar (GPR) has evolved over the years as a profound sensor-based investigation technique operating in a wide range of frequencies ranging from 250 to 1000 MHz and utilizing interaction of electromagnetic waves with subsurface to obtain a pseudo-image of the strata. Often due to constructional negligence and poor standards of construction, the pavement so constructed lacks structural strength and have poor compaction of construction material resulting into air pockets. During rainy season, water seeps into the pavement resulting into settling of sand and gravel underneath the pavement. Hence, when a heavy vehicle crosses over the road patch, it results in subsidence of that patch leading to casualties and property damage. In the present study, a system is developed for classification and identification of hazardous zones on a GPR image that can result in subsidence during rainy season. The system works on extraction of features from GPR response using discrete Fourier Transform. The GPR data collected at two sites in IIT Roorkee campus using 1 GHz antenna are fed to the support vector machine for training the classification system. It has been observed that presence of clay and trapping of water beneath the pavement resulted in subsidence of the patch. From the study, it can be deduced that the GPR can be used as a non-destructive tool for hazardous zone identification and pavement fault detection.

Index Terms—Discrete Fourier Transform (DFT), ground penetrating radar (GPR), hazardous zones, Non-destructive evaluation, support vector machine (SVM)

I. INTRODUCTION

Ground penetrating radar (GPR) has been extensively used for mapping the subsurface utilities and infrastructure [1]. With the development of high end and user-friendly electronics and increased ease of access, GPR has found its application in large number of fields ranging from study of glaciers, biomass mapping, contaminant mapping, saltwater intrusion detection, and quality assurance of newly laid asphalt pavement to subsurface infrastructure mapping [2]. One of the latest applications of GPR is in disaster management and assessment. Over the past few years, researchers have used GPR to find the signs of life buried in debris of collapsed buildings after earthquake, since GPR works on the interaction of electromagnetic (EM) waves with the material present in the subsurface; hence, properties such as dielectric constant and the binding between the material play a major role to modify the GPR response, i.e., the reflected signals from the subsurface anomalies [3].

From past many years GPR is widely used to monitor the pavement structures and anomalies present in it. For example, GPR is effective in revealing near-surface voids resulting from consolidation and erosion of the base material [4]. Voids are often responsible for weakening of the pavement structure, subsequently resulting in collapsing of the pavement. Kentucky Transportation Center used GPR to determine subgrade condition beneath settling concrete pavement [5].

Due to poor standards of construction maintained by the contractors, often the pavement constructed are poorly compacted with air voids and clay in them [6]. During the rainy season, water seeps into the ground inducing the settling of poorly compacted sand and gravel. The upper layer of concrete laid to construct the road network loses its strength, thus when a heavy transportation vehicle such as an earthmover or tanker crosses over it, the pavement collapses due to

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Received: December 4, 2023

Revision Requested: January 30, 2024

Last Revision Received: March 15, 2024

Accepted: April 20, 2024

Publication Date: May 17, 2024

DOI: 10.5152/electrica.2024.23186

land subsidence, which at times can be hazardous in nature. This creates a profound requirement for a system capable of detecting entities beneath the ground surface without destructive means where GPR presents utmost applicability [7]. The latest evidence indicating these treacherous construction quality lapses were visible in numerous parts of India [8–10]. At high speeds, these road collapses often turn fatal [11].

In the present study, a technique has been presented to identify such accident-prone zones in the road network by studying the spectral response of ground-coupled GPR and the obtained radargram using a 1 GHz antenna and then using support vector machine (SVM) to classify regions into safe and unsafe categories [12]. So that, these faulty patches which can potentially collapse under natural circumstances (such as stress due to heavy vehicles, subgrade subsidence due to rainfall) can be identified beforehand.

India is a country that relies heavily on road infrastructure network for meeting its transportation needs. However, this infrastructure network is highly infested with potholes which are a result of subsurface subsidence post pavement construction [13]. Despite India hosting such a large road infrastructure, no proper indicators are present to monitor the pavement conditions post construction [14]. Absence of key performance indicators for pavement monitoring post construction results in poor road maintenance which ultimately results in potholes. In India, potholes are one of the major causes of road accidents resulting in fatalities. As per an estimate, the social cost of road accidents in India is about 3% of its GDP [15].

Ground penetrating radar is a promising technology that uses a high volume of remotely sensed sub-surface data and has shown great potential as an effective tool for non-destructive evaluation of highway structures [16]. Furthermore, India is in urgent need of data-enabled pavement evaluation techniques for rapid pavement evaluation owing to its large and ever-busy road infrastructure network [17]. It has been observed that after the removal of ground bounce and cross talk from the acquired GPR data through pavement survey, frequency-based features could be determined. Ground penetrating radar utilizes EM waves for studying the subsurface structure. Electromagnetic waves are prone to attenuation. The attenuation increases or the depth of penetration inside the sub-surface structure decreases as the EM wave frequency increases (the depth of penetration of EM waves is inversely proportional to the square root of its frequency).

$$\partial = \sqrt{\frac{\rho}{\pi . f . \mu}} \quad (1)$$

where ∂ is the depth of penetration, f is the EM frequency, and μ is permeability. Ground penetrating radars in sub-surface pavement evaluation find their usage for study of depths ranging from 0 to 2.5 m. In India, even the newly constructed pavements find their thickness in the range of 1 to 1.5 m. Therefore, in the present study, GPR finds its suitable efficacy despite the fact that it potentially faces threats of attenuation with an increase in sub-surface depth.

This research work utilizes these frequency-based features for automatic classification of pavements using GPR as a cost-effective, fast, and reliable non-destructive pavement evaluation technique [18, 19]. Especially in countries such as India, where road network completion takes considerable amount of time, destructive evaluation of pavements would only delay the public access to these primary infrastructure components.

II. STUDY AREA

The aim of the study is to develop an effective method of identifying weak zones in the rigid pavement constructions in the Indian scenario. The construction quality of roads developed by small contractors is of no standards and is always prone to get washed away in the first rains or get collapsed after rains.

Two survey sites were constructed to simulate the two types of construction standards (one as per the ASTM standards while the other without following any construction standards), one a rigid pavement with steel rebar and a proper mesh structure of steel bars placed at regular intervals to provide physical strength to the pavement to bear heavy loads. The mesh size observed was 16 cm × 16 cm which is in accordance with construction norms of placing a mesh size of less than 20 cm × 20 cm if reinforcement is to be placed in concrete roads. A Type I cement ideal for pavements and precast construction was used. As per ASTM standards, a curing time of a minimum 7 days was observed.

The second site, i.e., site 2, was prepared with lesser accuracy, rare reinforcement structure with steel mesh present at isolated sites only, no mixture proportions maintained, which is the general scenario in Indian conditions. The cement used was type I cement and curing time observed as per ASTM standards of minimum 7 days.

The sites were GPR test sites and for the validity of the developed methodology, an occurrence of rain was necessary. The roads were constructed in the month of October after the rainy season was over, and the winter season was about to start in a view of testing the sites when the precipitation occurs in northern India due to cyclonic storms originating in the Mediterranean basin. These storms bring rainfall, a sudden drop in temperature, and cloudiness. The time gap between rainfall and construction was enough for both the structures to attain the maximum possible strength.

Just mid-way in January, heavy rainfall occurred for two consecutive days as expected due to the cyclonic storms. The site was ready to be tested. The data were collected on both road types,. the reinforced one and one without reinforcement. After the data were collected to test the structural strength, a heavy earth-moving vehicle with almost full capacity was made to move on both the road structures by a highly experienced test driver having experience of testing the runway pavements. The rigid pavement with reinforcement stood firmly with no structural flaws. The other pavement, as expected collapsed when the vehicle was moving over it. Analysis of the GPR data collected is discussed in the next section along with detailed methodology.

The GPR test sites are marked in Fig. 1:

a) Site 1 was developed near Hill View Apartments, a residential complex in IITR campus. The site contained rigid pavements without reinforcement structure; the site was suspected to be of weaker structural strength. Since the site was a specially prepared test site, no heavy earth-moving vehicles were allowed to run over it to prevent any mishap. This is a common phenomenon in India and prevalent in abundance. The work is completely outsourced on a turnkey basis, like private contractors and their nexus [20].

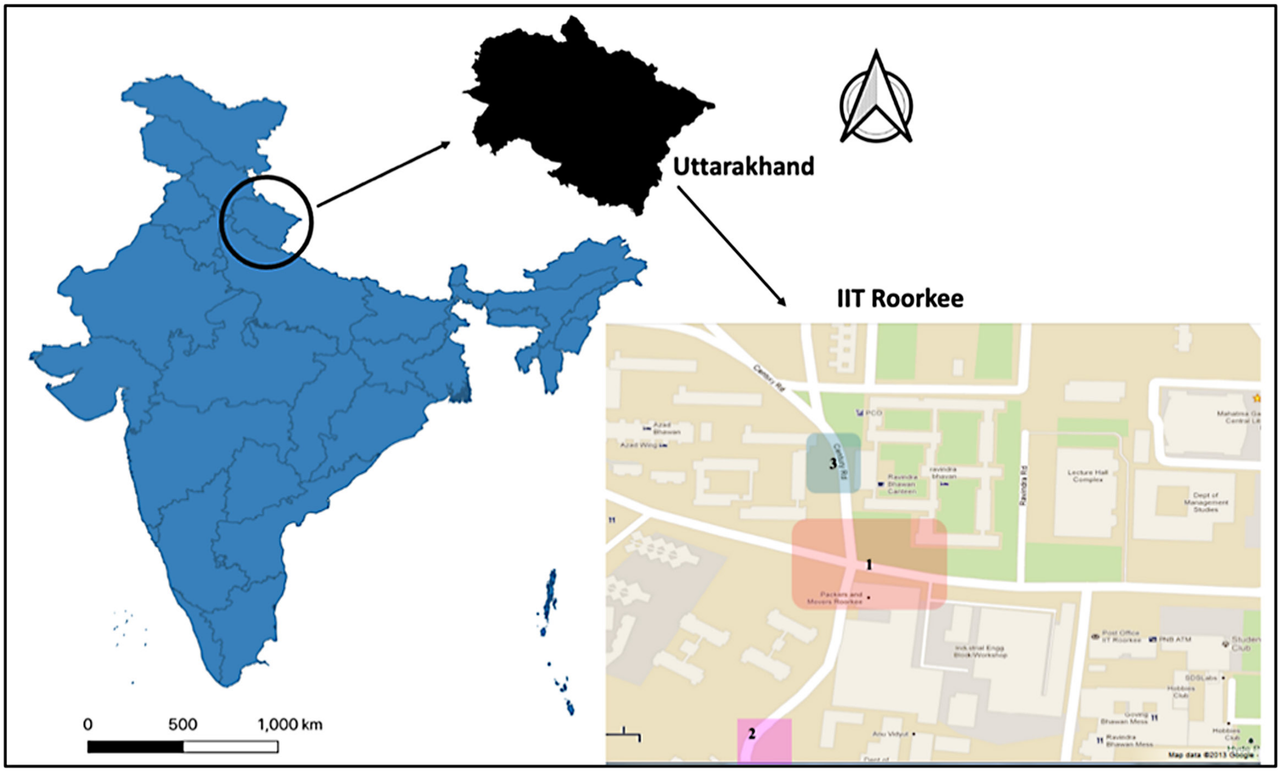


Fig. 1. Location of the survey sites. Site 1 highlighted in red color is used for collection of multi-date GPR data; site 2 highlighted in pink color has rigid pavement with reinforcement; site 3 highlighted in blue color has similar constructional structure.

b) Site 2 was developed as a connecting road to Hill View Circle and the Biotechnology Department in IITR campus, and the site contained a rigid pavement structure with reinforcement. Since the site was prepared as per standards, it was open for any kind of traffic.

c) Site 3 is the road near Azad Bhawan, students' hostel in IITR campus. It is another already constructed rigid pavement structure. The data collected over the site will be used for testing the developed methodology, hence no data collected on this site will be used for training purposes.

From Fig. 2, a GPR profile collected over site 1 after rainfall before subsidence, it is evident from multiple reflections that site is not up to the standards as one can notice multiple reflections due to uncompacted building materials. Ground penetrating radar waves interact with loose soil and multiple reflections as well as the traversing of the waves occur [21]. These waves present multiple spectral signatures and are essential for their efficient quantification as well as analysis. Fig. 3 shows the subsidence of site 1 after rainfall. A detailed discussion of the probable cause and reason for subsidence is discussed in sections 3 and 4.

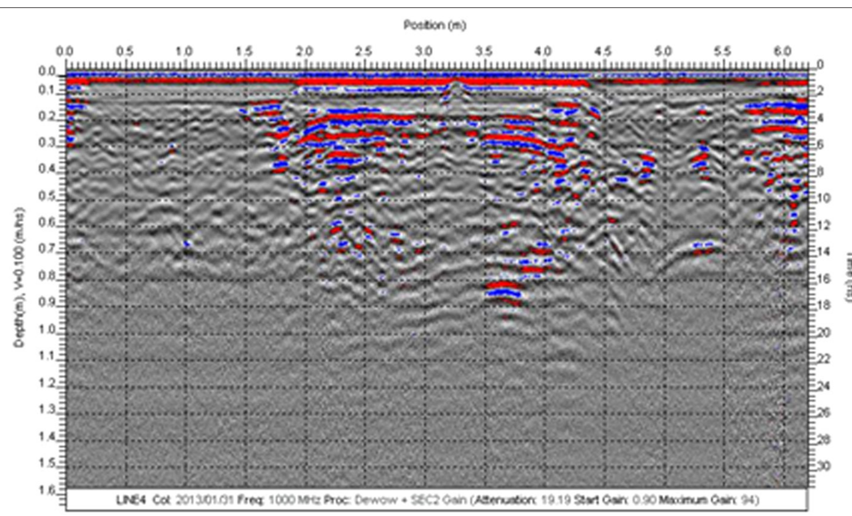


Fig. 2. GPR profile collected at site 1 using 1 GHz antenna before subsidence.

Fig. 3. Land subsidence at site 1 after rainfall.

III. METHODOLOGY

Ground penetrating radar employs EM waves to detect subsurface anomalies. An EM wave propagating in the ground is partially reflected when it hits the material whose dielectric properties are different from surrounding materials [22]. By analyzing the spectral signature of the reflected EM wave, it is possible to identify the objects. When GPR survey of a particular road network is carried out, the reflected echo signals or the GPR response from different materials possess different EM characteristics as different materials interact differently with the wave or particular resonance frequencies arising in the wave. Hence spectral analysis technique discrete Fourier transform (DFT) can be utilized to extract features from the response. The features so extracted would be input to a classification system to classify the signals. Fig. 4 presents a schematic methodological block diagram of the mentioned process.

A block diagram of the GPR system is shown in Fig. 5. The GPR antenna system shown in Fig. 4 is a ground coupled commercially available and mass produced GPR antenna system of Sensors and Software make, the model being GPR Noggin. Its working through Fig. 4 can be understood via the points depicted below.

- The GPR antenna system was a cart-based system, not a pull-based system, and was equipped with an electronic odometer that helped the pulse triggering mechanism to fire the EM pulse after a specified distance was traveled by the cart.
- The subsequent step was the data acquisition process. This involved the collection of data over the test bed in dry and wet conditions.
- After the data acquisition process, the acquired A-scans (GPR signals returning as a result of interaction of EM pulse with sub-surface anomalies) were imported in the MATLAB environment. Later, the features were extracted from these A-scans using DFT.
- After the feature extraction process, the selected features were used to train the SVM model.
- Using this trained model, the pavement was classified into two categories.
- The same process was repeated for the repaired test bed.

The diagram in Fig. 5 further depicts that after the waves reflected from the different layer boundaries are captured and stored in the system, they are now ready to be processed to extract information out of it. The GPR signal is partially reflected from each layer of the road. In the normal case, due to the coarser resolution of the GPR system, these signals are analyzed as a single signal. If these signals can be resolved separately using high-resolution algorithms such as the MUSIC algorithm, then it would help in characterizing the road layer features [23]. The features are extracted first by time to frequency transformation using the DFT algorithm (represented by time to frequency conversion) [24]. The strength of the Fourier coefficients corresponding to frequency has been used for training purposes. After

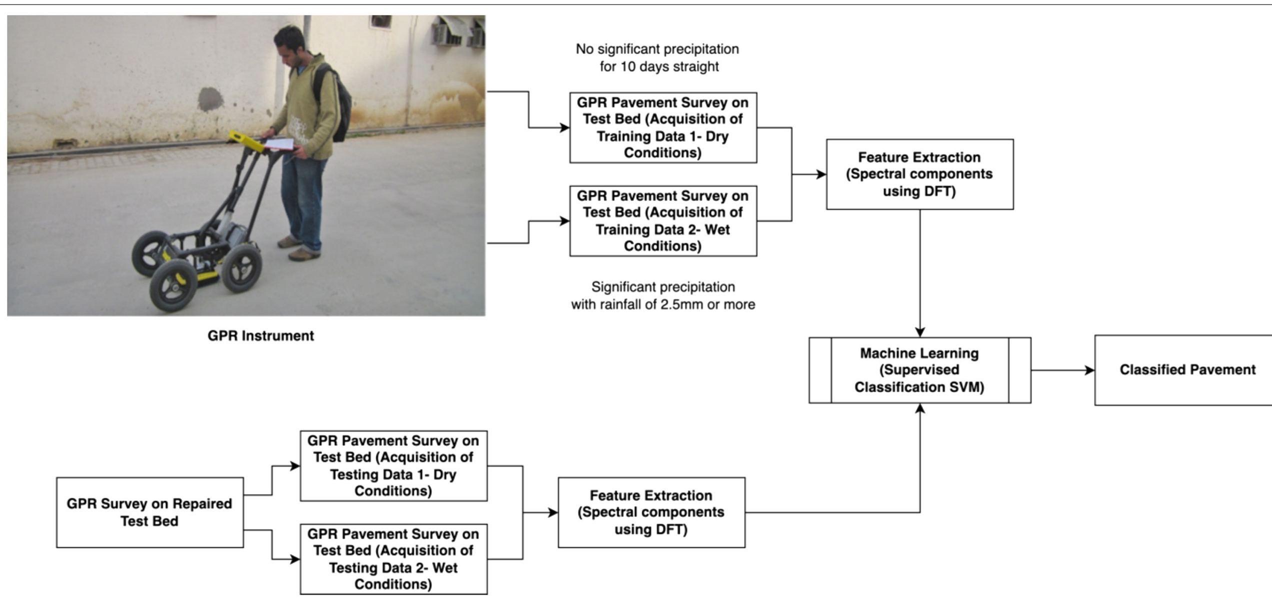


Fig. 4. Methodological flow.

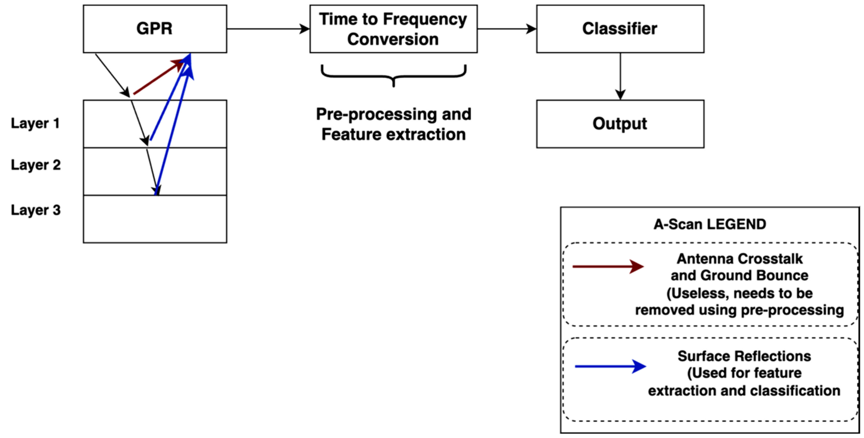


Fig. 5. Block diagram of the feature extraction and classification system.

the training is completed, the raw data collected has been classified using the above-trained machine learning approach.

A. Pre-processing and feature extraction

Ground penetrating radar response (A-scan, EM waves received by the GPR receiving antenna after interaction of fired EM pulse from the GPR transmitting antenna) obtained by conducting GPR survey contains low frequency signal components, which distorts the frequency spectra of the signal. The presence of low frequency components in the GPR response signal is known as "wow." If wow is not removed, it would distort the frequency spectrum of the GPR response, which may lead to false prediction of the nature of the pavement; hence, removal of direct current component and dewowing, i.e., removing of wow-effect is the first step. After pre-processing has been done, GPR response is subjected to time to frequency transformation using DFT.

Feature extraction using DFT: Let r[n] be the received response signal with minimized ground effects, where *n* is the number of time samples taken and depends on the sampling frequency of the GPR system, which is nearly ten times the central frequency of the GPR antenna, e.g., a 1 GHz antenna sampling rate being 10 GHz. So, the discrete Fourier transform of the received signal *x(n)* would be

$$X(k)=\sum_{n=0}^{N-1} x(n).e^{\frac{-j2\pi kn}{N}} \tag{2}$$

where *n* is 0 to *N-1*, *N* is the number of samples in an A-scan, and *x(n)* is an A-scan.

The response signals received from a properly compacted region would possess different spectral characteristics than that received from the fault zone [25]. Hence, the magnitude/dominating coefficient of the transform can be used for training the classification system.

B. Classification

Originally, SVM was formulated for two-class classification problems [26]. Support vector machine is a supervised machine learning algorithm used for classification tasks, including two-class problems. The primary objective of SVM is to find the optimal hyperplane that separates the data into classes while maximizing the margin between the classes [27]. Support vector machine finds the optimal hyperplane that maximizes the margin between classes in a high-dimensional space, aiming to correctly classify data points. Support vector machine can handle linearly separable and non-linearly separable data using kernel functions. It minimizes a cost function while ensuring correct classification or controlled misclassification through regularization. Support vector machine's advantages include effectiveness in high-dimensional spaces, resistance to overfitting, and ability to handle non-linear decision boundaries. However, its performance depends on kernel and regularization parameter choices.

This learning strategy is known to increase the generalization capability of the classifier. Fig. 6 portrays the adapted SVM classification technique for the classification of GPR traces as per their identified features.

IV. RESULTS AND ANALYSIS

The GPR A-scans were first pre-processed to remove antenna cross talk and ground bounce. This pre-processing reduced useless high-amplitude signals from the data [28]. The result of pre-processing has been presented in Fig. 7.

Before conducting spectral analysis of the radar responses, ground bounce, i.e., strong return due to the first reflection of EM waves and antenna cross talk, i.e., direct coupling of EM waves between transmitter and receiver was removed so as to highly enhance the visual aesthetics of the image spectra [29, 30].

Ground penetrating radar profile was collected at three sites and was pre-processed as per the aforementioned pre-processing techniques with an aim to monitor the pavement structural conditions of the newly constructed test bed. The results so obtained are discussed below:

i. The GPR profile collected over the patch at site 1 differs largely from the GPR profile collected at site 2. The GPR profile collected over the patch at site 1 before subsidence after rainfall is shown in Fig. 7, while the GPR profile collected at site 2 after rainfall is shown in Fig. 8. In the profiles, the *Y*-axis represents the depth while the *X*-axis represents the distance traveled by the cart in cm. The profile is color coded depending upon the intensity of radar reflection recorded by the receiver. The red-colored pixels being the highest positive intensity while blue-colored ones

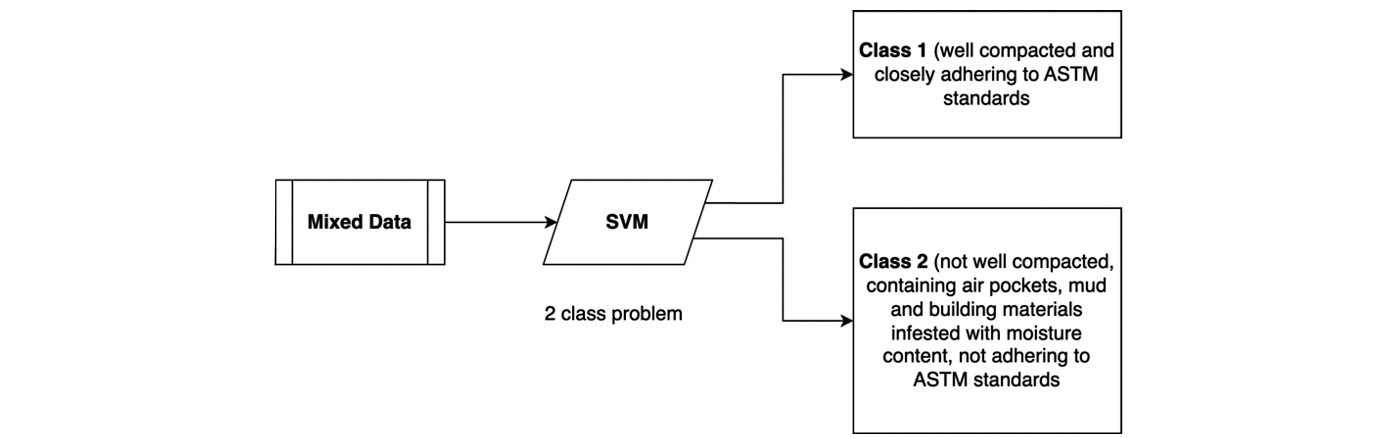


Fig. 6. Adapted SVM classification technique.

represent the highest negative intensity. The rebar (steel reinforcement bars in the rigid pavement) in the GPR profile is interpreted by the identification of the honeycomb structure [31]. They are marked using two parallel black lines in Fig. 8.

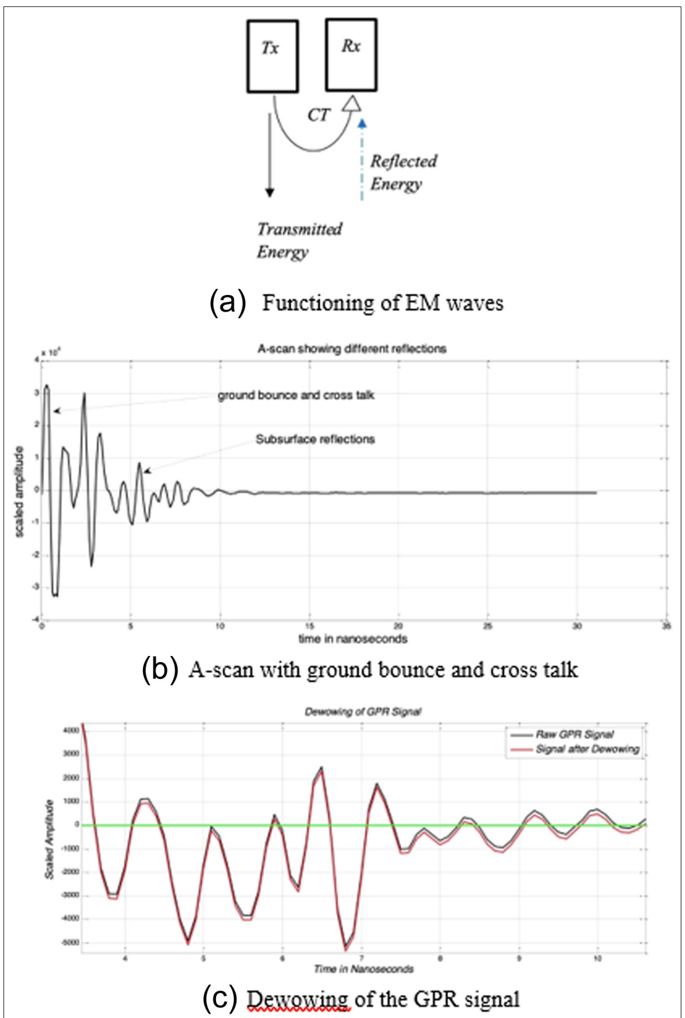


Fig. 7. A-scans with cross talk and ground bounce with dewowing.

- When Figs. 8 and 9 are compared, it is found that the pavement structure at site 2 is rebar reinforced while that at site 1 is not. Hence, it can be deduced that the pavement at site 1 lacks structural strength as a cement-concrete pavement as it is not rebar reinforced.
- By analysis of Fig. 8, it is evident that the layers at site 1 are not stratified, and strong reflections are received from them, as GPR works on the principle of contrast of dielectric properties of medium hence there must be a sudden large change in the relative permittivity of the medium [32]. The medium can be concrete–air–concrete or concrete–clay–concrete [33]. There is not much variation in the relative permittivity of air (relative permittivity = 1) and concrete (relative permittivity ranges from 2 to 2.6). Hence, the possibility of concrete–air–concrete interface is less [34–36].
- Before the subsidence of patch at site 1, there was rain in the Roorkee city for past 2-3 days. Since the pavement was poorly constructed, there might be a possibility that rain water instead of running away from the pavement gets trapped beneath it, resulting in the formation of muddy mixture of construction material such as poorly compacted sand and clay. Hence, if water is seeping into the structure, then the relative permittivity of the medium is bound to increase due to increase in moisture content in the medium, which can be a possible cause of very strong reflections from the medium [37]. Fig. 10 shows an example of the aforementioned condition.

After subsidence, to check for its probable causes, the site was again prepared with the same type I cement [38], no reinforcement, and giving a minimum curing time of 7 days as per ASTM standards [39]. Fig. 11 portrays the commencement of repair work.

However, the layers were compacted well this time using hand tamper followed by vibrating plate compactors to facilitate layer-by-layer compaction. Use of hand tamper before vibrating plate compactor allowed the layer to compact without forming air pockets. Direct use of vibrating plate compactor on damaged surfaces poses a risk of air pocket formation [40]. Data were collected only after pouring water at a rate of approximately 3000 L/h for 5 hours using rain pipes on the repaired patch to simulate rainfall conditions. Ground penetrating radar profile was taken again on the road patch at site 1 after it is properly reconstructed using proper compaction and curing techniques, as shown in Fig. 12.

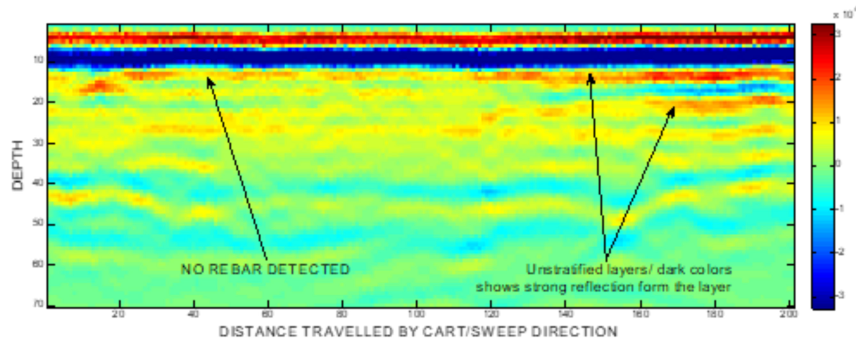


Fig. 8. GPR profile collected over the faulty patch at site 1 before land subsidence showing absence of rebar.

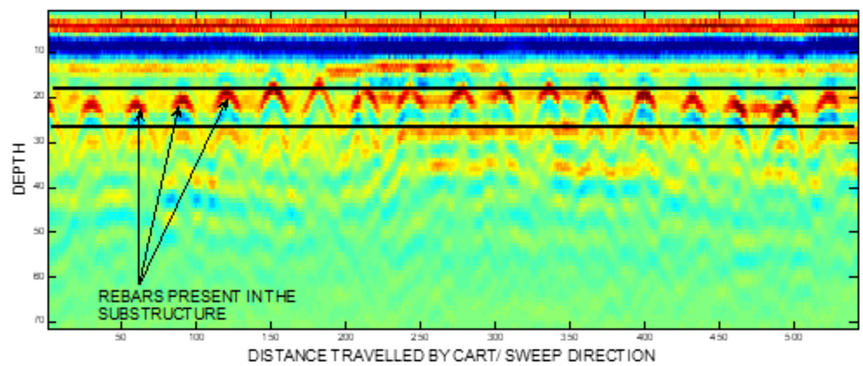


Fig. 9. GPR profile collected at site 2 showing presence of rebar.

Through visual interpretation of Fig. 12, it was evident that now the layers are more stratified and the number of strata can be easily counted with no sign of sharp reflections due to a sudden change of wave traveling medium [41].

All the observations presented above are based on the visual interpretation of the GPR profiles obtained through pavement surveys.

Fig. 10. Cement concrete pavement with visible cracks allowing percolation of rainwater at IIT Roorkee.

Therefore, to reach a proper conclusion related to pavement evaluation, spectral analysis of the GPR response was performed. Now, the response over the repaired patch and the response over the patch before land subsidence after rainfall (at site 1) was taken and was converted to frequency domain using DFT. Fig. 13 shows the comparison of the spectral response of the two traces.

It can be observed from Fig. 13(a) that the frequency response of the trace collected after repairing shows dominant behavior toward higher frequencies, while the trace collected over patch before land subsidence shows dominant behavior toward lower frequencies. By observing the spectral response of the two traces, it can be deduced that the reason for the subsidence might be the presence of clay and trapping of water beneath the pavement (top visible cement concrete layer and subgrade). The presence of clay and water attenuates the EM waves and induces low-frequency components in the GPR response as higher frequencies are attenuated faster. The seeping water increases the conductivity of the medium (attenuation is directly proportional to the frequency and conductivity of the medium). The phenomenon can be understood by equation 3.

$$\alpha = \frac{1}{\sqrt{f\sigma\mu\pi}} \quad (3)$$

where f is the frequency of the wave fired by the GPR, σ is the conductivity of the medium, and μ is the magnetic susceptibility.

The presence of moisture beneath the concrete layer and above the subgrade at site 1 can also be confirmed via spectral response of GPR signal obtained in Fig. 13 (b). The before and after rainfall spectral

Fig. 11. Commencement of repair work at site 1.

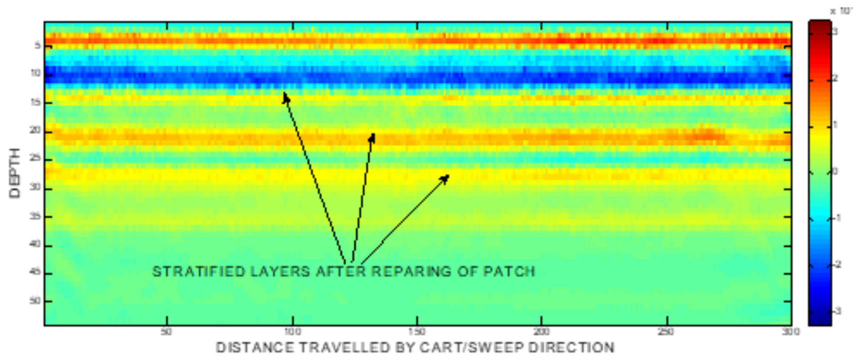
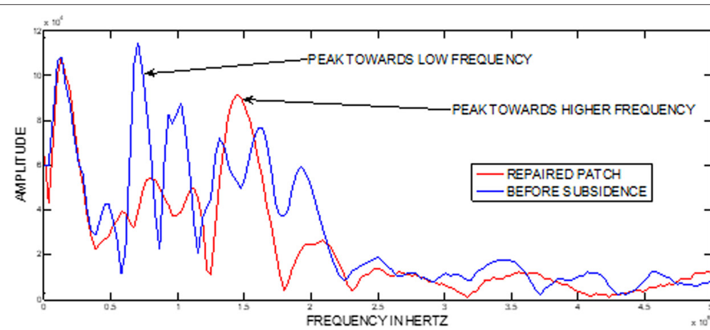
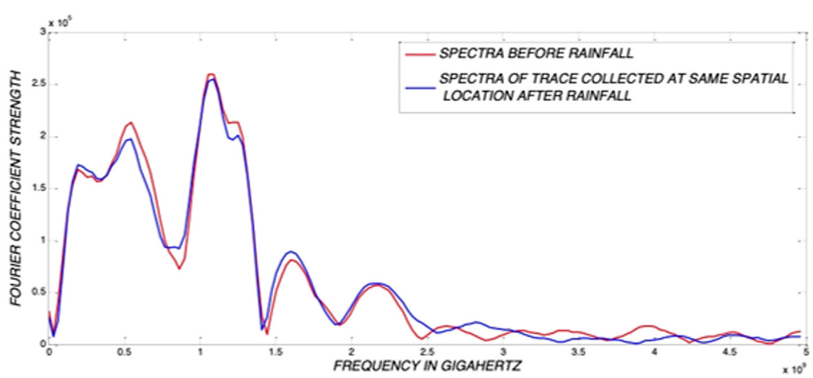


Fig. 12. GPR profile over a patch at site 1 after reconstruction showing stratified layers.



(a) Spectral response of the traces collected after repairing and before subsidence at road patch at site 1



(b) Spectral response of the traces collected at site 3 before and after rainfall which is rebar reinforced

Fig. 13. Spectral response of GPR signals at site 1 and site 3.

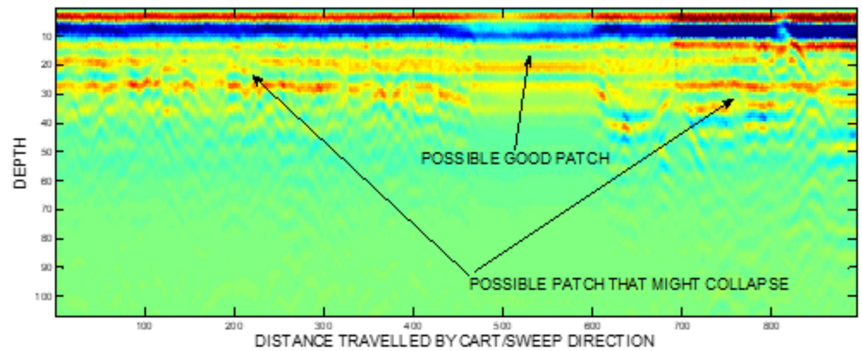


Fig. 14. GPR profile collected at site 3.

signatures at this site are almost identical. No attenuation of higher frequency and introduction of lower frequency components indicates that even after rainfall in a well-compacted, rebar-reinforced, and ASTM standard-based cement concrete pavement gets minimal water intrusion.

Now, using spectral response as an attribute, a system is developed to classify the pavements present in IIT Roorkee campus. Another GPR profile is collected at site 3 as shown in Fig. 14. It is found that this pavement structure also lacked reinforcement.

Using the SVM trained with GPR data collected over the patch at site 1 before land subsidence and after repairs, the GPR radargram collected at site 3 is classified. Fig. 15 shows the result of the SVM classification.

The obtained classified radargram contains black and white portions. The white portion in the radargram depicts that the pavement has been compacted properly and there is minimal water intrusion in the pavement structure or the water drained off away from the pavement. While the black portion of the radargram depicts that the pavement structure is poorly compacted and after rainfall, it may have a tendency to clog the water beneath it. Thus, leading to the formation of clay and thereby resulting in the settlement of construction material, which ultimately leads to pavement subsidence.

A. Contributions of the Study

The specific contributions of the study have been listed below:

- The research work focuses on identification and classification of sub-surface subsidence using non-destructive techniques under Indian use case scenarios. Indian road infrastructure is one of the biggest in the world. Maintenance and supervision of this humongous infrastructure is always a tedious task. This calls for a fast automated technique that can deliver reliable results for monitoring pavement structures. At present, the systems utilized for monitoring Indian pavements rely heavily on destructive monitoring techniques. This leads to diversion of traffic, partial closure of road segments, and high monitoring costs which should be site-specific. The present work enables the GPR system to monitor stretches of the road network in a fraction of the time as compared to destructive monitoring techniques, thereby saving costs incurred on monitoring the road network.
- The research work utilizes SVM for automatic classification of GPR signals for identification of probable road patches that could subside in case of heavy precipitation. Use of SVM reduces the mathematical complexity involved in GPR signal classification. Support vector machine techniques are best suited for two-class problems which is a case of this research work (*viz.* classification of area which can subside and the area which appears healthy). If in future, a standalone system need to be deployed that classifies the GPR signals in real time, then, SVM will result in reduced hardware requirements as compared to AI-based standalone signal classification system.
- In India, monitoring and supervision of pavement structures is often outsourced to a third party. These third parties employ semi-skilled professionals to reduce the operational cost associated with the process. Destructive techniques for pavement

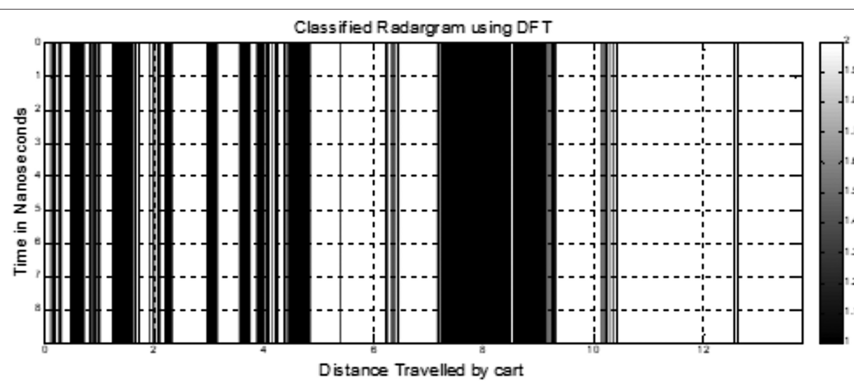


Fig. 15. Classified radargram using DFT (white shows compacted patch, black shows faulty patch).

monitoring require a skill above semi-skilled professionals for efficient interpretation of results. The developed technique portrayed in this research work provides classified results based on system learnings. As these results are presented only in two possible ways, the interpretation of results becomes an easy task. This results in lesser dependency upon human skills. This can thereby result in better pavement monitoring efficacy.

VI. CONCLUSION

Ground penetrating radar can be an effective tool to identify the hazardous zone or the structurally weak pavement zone that might collapse when heavy vehicle crosses it. Visual interpretation of the GPR profile also known as B-scans only gives the information about the type of layers present underneath the structure. The visual profiles or the collection of A-scans into B-scans do not reveal the probable cause of reflection. Absence of spectral components in the B-scans limits the usability of B-scan and increases the dependency upon trained human resources capable of interpreting these profiles through their experience. To facilitate swift interpretation of GPR data, it is necessary to transform it into a domain which reveals feature-bound information. Frequency transformation is one such domain. Transformation of a GPR signal into the frequency domain helps in determining the various frequency components present in the signal. As the EM waves interact differently with different materials, the reflection of EM waves from medium-to-medium boundary develops frequency signatures that represent a medium almost uniquely.

Hence, analysis of the spectral response of the GPR data collected over the profile can help determine the type of material present underneath the structure and whether the structure possesses necessary structural components such as steel rebar mesh and the compacted subgrade. Formation of clay or mud and trapping of water beneath the subsurface give rise to attenuation of high-frequency components of EM waves.

- The findings of the study indicate through frequency analysis of the returned response that the domination of low-frequency component in the case of GPR signal interacting with high-frequency attenuating mediums such as clay, mud, and moisture.
- Other findings of the study indicate that well compacted subgrade-based cement concrete pavement poses a GPR spectral profile free from high magnitude low frequency components and a visible shift of frequency spectra toward higher frequency components.
- As a specific finding, it can be stated that higher frequency components observed in GPR profiles obtained even after natural phenomena like rainfall are sure indicators of well-compacted subgrade and cement concrete laid by following proper construction standards. Hence, it can be effectively identified by the analysis of the spectral response of the GPR signal. Pavement structures infested with sub-surface subsidence due to rainfall pose high threats as compared to visible potholes because they are not clearly visible. They are camouflaged as a perfect pavement structure but instead, it is only a top base with no underlying sub-base support. In such cases, when a driver drives over these infested pavement structures, the momentum of the vehicle along with the sudden subsidence of these infested pavement structures results in fatal road accidents. This study can reduce such fatal incidents comprehensively.

The study finds that the major cause of subsidence or failure of pavement structure was due to poor compaction of layers, trapping of water underneath the pavement, and formation of clay that weakens the pavement. Such structural formations weaken the already weak pavement structure devoid of reinforcement. Support vector machine-based machine learning techniques for processing GPR signals not only assist in effective, non-destructive, fast, and reliable classification of pavements but also minimize the requirement of trained manpower for GPR operations. The developed technique inherits the advantage that the incoming RADAR data could be processed in real time using autonomous vehicles, thereby further reducing the need for manpower and time for pavement evaluations.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – R.D.G.; Design – U.J., N.S.; Supervision – R.D.G., V.K.J., K.S.; Resources – R.D.G.; Materials – V.K.J., K.S.; Data Collection and/or Processing – U.J., N.S.; Analysis and/or Interpretation – U.J., N.S.; Literature Search – U.J.; Writing – N.S.; Critical Review – U.J., N.S., R.D.G.

Declaration of Interests: The authors have no conflicts of interest to declare.

Funding: The authors declare that this study received no financial support.

REFERENCES

1. R. Knight, “Ground penetrating radar for environmental applications,” *Annu. Rev. Earth Planet. Sci.*, vol. 29, no. 1, pp. 229–255, 2001. [CrossRef]
2. T. Wang, J. M. Keller, P. D. Gader, and O. Sjahputera, “Frequency subband processing and feature analysis of forward-looking ground-penetrating radar signals for land-mine detection,” *IEEE Trans. Geosci. Remote Sens.*, vol. 45, no. 3, pp. 718–729, 2007. [CrossRef]
3. Z. Leng, and I. L. Al-Qadi, “An innovative method for measuring pavement dielectric constant using the extended CMP method with two air-coupled GPR systems,” *NDT E Int.*, vol. 66, pp. 90–98, 2014. [CrossRef]
4. R. Antoine, C. Fauchard, Y. Fargier, and E. Durand, “Detection of leakage areas in an earth embankment from GPR measurements and permeability logging,” *Int. J. Geophys.*, vol. 2015, pp. 1–9, 2015. [CrossRef]
5. K. Vargas, “Non-destructive GPR technology saves time and money on transportation infrastructure repairs,” *GSSI Geophysical Survey Systems, Inc.* Available: https://www.geophysical.com/non-destructive-gpr-technology-saves-time-and-money-on-transportation-infrastructure-repairs. [Accessed: September 06, 2023]
6. R. Guo, T. Nian, and F. Zhou, “Analysis of factors that influence anti-rutting performance of asphalt pavement,” *Constr. Build. Mater.*, vol. 254, p. 119237, 2020. [CrossRef]
7. W. Wai-Lok, X. Dérobert, and P. Annan, “A review of Ground Penetrating Radar application in civil engineering: A 30-year journey from locating and testing to imaging and diagnosis” *NDT E Int.*, vol. 96, pp. 58–78, 2018. [CrossRef]
8. *Times of India*, “road collapse India - Google Search.” Available: https://www.google.com/search?q=road+collapse+india&rlz=1C5CHFA_enIN1012IN1012&oq=road+collapse+india&gs_lcrp=EgZjaHJvbWUyBggAEEUYOTIGCAEQRRg70gEIMjA0NWowajeoAgCwAgA&sourceid=chrome&ie=UTF-8#fpstate=ive&vld=cid:8ab46a62,vid:vLRO_N5K4Vc. [Accessed: September 06, 2023].
9. *Times of India*, “Ahmedabad’s Mumatpura deck collapse due to poor concrete, negligence: Inquiry report | Ahmedabad news - Times of India.” Available: https://timesofindia.indiatimes.com/city/ahmedabad/ahmedabads-mumatpura-deck-collapse-due-to-poor-concrete-negligence-inquiry-report/articleshow/98463466.cms?from=mdr. [Accessed: September 06, 2023].
10. “Part of road collapses in Kharghar during excavation, heavy rainfall,” 2023, *The Times of India*. Available: https://timesofindia.indiatimes.com/city/navi-mumbai/part-of-road-collapses-in-kharghar-during-excavation-heavy-rainfall/articleshow/101426795.cms?from=mdr. [Accessed: September 06, 2023].
11. DNAIndia, *“Portion of Highway Collapses in Himachal Pradesh, CM Jai Ram Thakur Orders Probe.”* Available: https://www.dnaindia.com/india/

report-portion-of-highway-collapses-in-himachal-pradesh-cm-jai-ram-thakur-orders-probe-2976205. [Accessed: September 06, 2023].
12. Z. Tong, J. Gao, and D. Yuan, "Advances of deep learning applications in ground-penetrating radar: A survey," *Constr. Build. Mater.*, vol. 258, p. 120371, 2020. [CrossRef]
13. A. Shtayat, S. Moridpour, B. Best, A. Shroff, and D. Raol, "A review of monitoring systems of pavement condition in paved and unpaved roads," *J. Traffic Transp. Eng. Engl. Ed.*, vol. 7, no. 5, pp. 629–638, 2020. [CrossRef]
14. M. Barffour, S. Gupta, G. Gururaj, and A. A. Hyder, "Evidence-based road safety practice in India: Assessment of the adequacy of publicly available data in meeting requirements for comprehensive road safety data systems," *Traffic Inj. Prev.*, vol. 13, pp. 17–23, 2012. [CrossRef]
15. GOI, "Road safety and traffic management,", 2007. [Online]. Government of India. Available: https://wbpwd.gov.in/files/contents/road_safety.pdf.
16. S. Guo, Z. Xu, X. Li, and P. Zhu, "Detection and characterization of cracks in highway pavement with the amplitude variation of GPR diffracted waves: Insights from forward modeling and field data," *Remote Sens.*, vol. 14, no. 4, p. 976, 2022. [CrossRef]
17. K. Bhalla, "Monitoring India's progress on road safety will require investment in data systems," *Lancet Public Health*, vol. 5, no. 2, p. e82, 2020. [CrossRef]
18. H. Zhou, and Y. Wang, "Time frequency representations for classification of landmine using UWB impulse GPR," in 4th International Conference on Wireless Communications, Networking and Mobile Computing. Dalian, China: IEEE PUBLICATIONS, Oct. 2008, 2008, pp. 1–4. [CrossRef]
19. L. Bianchini Ciampoli, F. Tosti, N. Economou, and F. Benedetto, "Signal processing of GPR data for road surveys," *Geosciences*, vol. 9, no. 2, p. 96, Feb. 2019. [CrossRef]
20. N. Sharma, and R. D. Garg, "Advanced transportation safety using real-time GIS-based alarming system for animal-prone zones and pothole areas," *J. Transp. Eng. Part A: Systems*, vol. 149, no. 4, p. 04023003, 2023. [CrossRef]
21. K. Zajícová, and T. Chuman, "Application of ground penetrating radar methods in soil studies: A review," *Geoderma*, vol. 343, pp. 116–129, 2019. [CrossRef]
22. W. Shao, A. Bouzerdoum, S. L. Phung, L. Su, B. Indraratna, and C. Rujikiatkamjorn, "Automatic classification of GPR signals," in *Proceedings of the XIII Internarional Conference on Ground Penetrating Radar*. Lecce: IEEE Publications, 2010, pp. 1–6. [CrossRef]
23. L. Wang, X. Gu, Z. Liu, W. Wu, and D. Wang, "Automatic detection of asphalt pavement thickness: A method combining GPR images and improved Canny algorithm," *Measurement*, vol. 196, p. 111248, 2022. [CrossRef]
24. L. Zhang, T. Ling, B. Yu, F. Huang, and S. Zhang, "Intensive interferences processing for GPR signal based on the wavelet transform and F-K filtering," *J. Appl. Geophys.*, vol. 186, p. 104273, 2021. [CrossRef]
25. W. Shao, A. Bouzerdoum, S. L. Phung, L. Su, B. Indraratna, and C. Rujikiatkamjorn, "Automatic classification of ground-penetrating-radar signals for railway-ballast assessment," *IEEE Trans. Geosci. Remote Sens.*, vol. 49, no. 10, pp. 3961–3972, 2011. [CrossRef]
26. K.-S. Goh, E. Y. Chang, and B. Li, "Using one-class and two-class SVMs for multiclass image annotation," *IEEE Trans. Knowl. Data Eng.*, vol. 17, no. 10, pp. 1333–1346, 2005. [CrossRef]
27. J. Cervantes, F. Garcia-Lamont, L. Rodríguez-Mazahua, and A. Lopez, "A comprehensive survey on support vector machine classification: Applications, challenges and trends," *Neurocomputing*, vol. 408, pp. 189–215, 2020. [CrossRef]
28. V. Salinas Naval, S. Santos-Assunçao, and V. Pérez-Gracia, "GPR clutter amplitude processing to detect shallow geological targets," *Remote Sens.*, vol. 10, no. 2, p. 88, 2018. [CrossRef]
29. S. Wang, Z. Leng, and X. Sui, "Detectability of concealed cracks in the asphalt pavement layer using air-coupled ground-penetrating radar," *Measurement*, vol. 208, p. 112427, 2023. [CrossRef]
30. V. G. Sugak, and A. V. Sugak, "Phase spectrum of signals in ground penetrating radar applications," in IEEE Radar Conference: IEEE Publications, 2009, pp. 1–5. [CrossRef]
31. G. Ghongade, K. P. Kalyan, R. Vaira Vignesh, and M. Govindaraju, "Design, fabrication, and analysis of cost effective steel honeycomb structures," *Mater. Today Proc.*, vol. 46, pp. 4520–4526, 2021. [CrossRef]
32. Y. Ma, X. Song, Z. Li, P. Tao, Q. Cao, and J. Tian, "A GPR segregation detection method on visual textures and dielectric properties," *IEEE Trans. Geosci. Remote Sens.*, vol. 61, pp. 1–12, 2023. [CrossRef]
33. A. Abramov, A. Sugak, and V. Sugak, "High order spectral estimation methods in ground penetrating radar applications," in International Kharkiv Symposium Physics and Engrg. of Millimeter and Sub-Millimeter Waves (MSMW), Kharkiv National University: IEEE, 2007, pp. 855–857. [CrossRef]
34. L. Jiao, Q. Ye, X. Cao, D. Huston, and T. Xia, "Identifying concrete structure defects in GPR image," *Measurement*, vol. 160, p. 107839, 2020. [CrossRef]
35. A. Joshaghani, and M. Shokrabadi, "Ground penetrating radar (GPR) applications in concrete pavements," *Int. J. Pavement Eng.*, vol. 23, no. 13, pp. 4504–4531, 2022. [CrossRef]
36. F. Tosti, and C. Ferrante, "Using ground penetrating radar methods to investigate reinforced concrete structures," *Surv. Geophys.*, vol. 41, no. 3, pp. 485–530, 2020. [CrossRef]
37. İ. Kaplanvural, K. Özkap, and E. Pekşen, "Influence of water content investigation on GPR wave attenuation for early age concrete in natural air-drying condition," *Constr. Build. Mater.*, vol. 297, p. 123783, 2021. [CrossRef]
38. S. Yousuf, P. Shafigh, Z. Ibrahim, H. Hashim, and M. Panjehpour, "Crossover effect in cement-based materials: A review," *Appl. Sci.*, vol. 9, no. 14, p. 2776, 2019. [CrossRef]
39. ASTM, "Building standards - Standards products - Standards & publications - Products & services." Available: https://www.astm.org/products-services/standards-and-publications/standards/building-standards.html. [Accessed: September 06, 2023].
40. H. Qi *et al.*, "Analysis on improvement effect of subgrade by dynamic compaction," *Arab. J. Geosci.*, vol. 14, no. 22, p. 2281, 2021. [CrossRef]
41. W. Shao, A. Bouzerdoum, and S. L. Phung, "Sparse representation of GPR traces with application to signal classification," *IEEE Trans. Geosci. Remote Sens.*, vol. 51, no. 7, pp. 3922–3930, 2013. [CrossRef]

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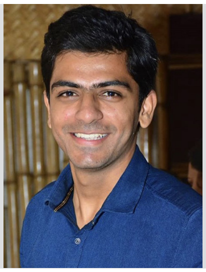

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