Grenze International Journal of Engineering and Technology, June Issue

Modern Trends in Non-Destructive Soil Compaction Assessment with a Novel Radio Wave–based Experimental Framework

Prashant Pande[1], Aditya Patle[2], Nilesh Turankar[3], Tejas Sakure[4], Ved Ghodkhande[5] and Vivek Prajapati[6]
[1]Assistant Professor, Department of Civil Engineering, Yeshwantrao Chavan College of Engineering, Nagpur, India
Email: pbpande@ycce.edu
[2-6]Student, Department of Civil Engineering, Yeshwantrao Chavan College of Engineering, Nagpur, India

***Abstract*— Assessment of the geotechnical and pavement structures are to be done as regards to the long-term performance of the soil compaction. The conventional methods of destruction are traditional like core cutters test and sand cones test which are time lasting, and point based. This essay talks about the design and the laboratory experiments of a new radio wave-based non-destructive testing (NDT) system in conjunction with machine learning techniques in predicting soil bulk density.**
Experiments on the laboratory conditions were conducted based on varying degrees of compaction and moisture content on prepared soil samples. Sensors parameters like Received Signal Strength Indicator (RSSI) and Signalto Noise Ratio (SNR) results were compared to laboratory bulk density data. The model of multiple regression and machine learning were implemented and compared in the measures of R^2 , MAE and RMSE. Random Forest model gave $R^2 = 0.9046$, RMSE = 0.0404 g/cc and MAE = 0.0308 g/cc which indicates that there is huge ability to predict and even generalize. The proposed system will enable real-time, cost-efficient, and non-destructive system of the soil compaction and enable intelligent quality control of the construction process.

***Index Terms*— Soil density, Soil compaction, Radio wave sensor, Non-destructive testing (NDT), Random Forest regression, RSSI.**

I. INTRODUCTION

The density of subgrade and soil compaction are significant parameters when analyzing the long term performance, shear strength, permeability, deformation properties etc. of earthworks and pavements. Due to the correct compaction, the shear resistance of the pavement will also be enhanced, and the pavement settlement will be reduced without the need to damage a sustainable infrastructure (e.g., embankments, railways, and highways) [1]. Dry density and optimum moisture content are the most widely used measures to determine whether a given compaction process meets the specifications or not based on the type of soil, gradation, compaction energy level and environmental conditions where reported density and optimum moisture content are the measures of interest [2].As part of the quality assurance of the construction and the associated performance-related circumstances of acceptance, the in-situ density is among the primary requirements [3].

Grenze ID: 01.GIJET.12.2.500_22

In addition to these conventional methods such as the Proctor testing, sand-cone, core sampling are current in terms of their reliability but they are numerically intensive, destructive and time consuming and only suitable in discrete locations of large construction sites [4]. These limitations restrict continuous monitoring and fail to capture spatial variability across large construction sites.

The growing demands of efficiency, sustainability, and immediate quality management have in turn stimulated the development of non-destructive testing (NDT), intelligent compaction and data-driven monitoring technologies. The given paper is going to offer a profound analysis of the classical, non-destructive, and AI-based methods of measuring soil density in addition to the newest technological advancements and research trends. An experimentally determined gap leads to a radio wave-based non-destructive method of measurement that is grounded on the measurement of soil density.

II. Intensive Review of Soil Density Measurement and Compaction Assessment Techniques

Dry density has been the focal point of complication performance, which directly manipulates the stiffness, shear strength, compressibility, and permeability of soils. In the majority of geotechnical requirements, it is necessary to meet a target percentage of maximum laboratory dry density in order to provide sufficient load bearing capacity and long-term stability. High density decreases the pore spaces and increases the soil-water retention behaviour and minimizes the diffusion of moisture which increases durability of compacted layers [5]. The challenge however is that it is very important yet field measurement is not very effective in variable soil and moisture conditions.

In-situ density assessment methods like the sand-cone testing and core cutter sampling are the conventional and accepted reference methods but have limitations on the complexity of the operations and localized sampling. The nuclear density gauges provide quick and relatively precise results regarding the wet and dry density, although their application is limited because of the radiation safety issues, licensing, and sensitivity to the calibration . Such constraints have encouraged a lot of research in indirect and sensor-based techniques, such as time-domain reflectometry, electrical resistivity, fibre-optic sensing, and penetrometer-based techniques. Although these methods enhance the speed of testing and minimize disturbance, most of them are based on empirical correlation and site-specific calibration. Figure 1 shows how the technology of the process of subsurface investigation has developed over the years, moving on to the more modern non-destructive testing (NDT) and even to intelligent, data-based sensing systems. This transition highlights increasing measurement sophistication alongside trade-offs in accuracy, cost, and operational complexity (Figure 1).

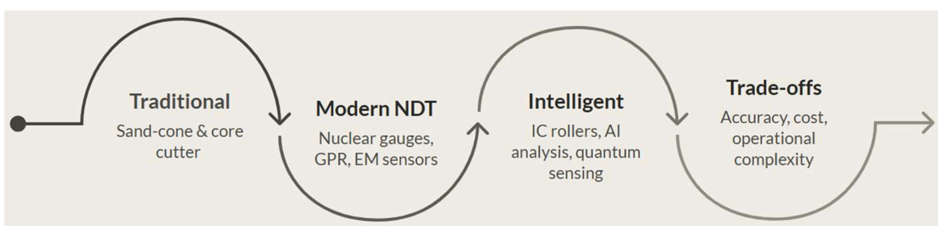

Figure 1. Evolution of Subsurface Investigation Techniques from Traditional Methods to Intelligent Sensing Systems

The trend of compaction assessment technologies consistent with a larger real time, intelligent, non-destructive approach to the monitoring systems. Techniques involving electromagnetic waves, including Ground Penetrating Radar (GPR), electromagnetic density gauges, and gamma-ray spectrometry have been gaining more and more popularity in characterizing subsurface. GPR technologies allow to quickly assess the dielectric characteristics, layer depth, moisture level, and mechanical characteristics of pavement and subgrades [6], [7]. However, their effectiveness is influenced by soil texture, moisture variability, and penetration depth limitations, particularly in clay-rich or saturated environments [8]

Recent studies focus on combined NDT systems where a combination of various sensing technologies is set up to enhance the diagnostic accuracy. The reliability of multimethod techniques using GPR, seismic methods, and electromagnetic sensors and impact imaging has proved to be more reliable than a single sensor technique in implementation [9], [10]. Electrical resistivity, which is verified using laboratory moisture density relationships, is also an effective measure to determine compaction state and water content [11], whereas Light Weight Deflectometers can be used to evaluate quality quickly based on stiffness [12]. Three-dimensional X-ray computed tomography is one of the high-resolution imaging tools that can improve the knowledge of the distribution of particles and voids in compacted soils [13]. In line with the perception of progress, intelligent compaction (IC) technologies have revolutionized the earthwork quality control through the ability to perform continuous spatial control with smart rollers that have GPS and onboard sensors ([9], [14], [15] Field studies confirm that IC systems significantly improve compaction uniformity and efficiency while reducing reliance on point-based testing [4], [6]. Combination of IC measurements with mechanistic frameworks has also made possible performance based quality management approaches [8].

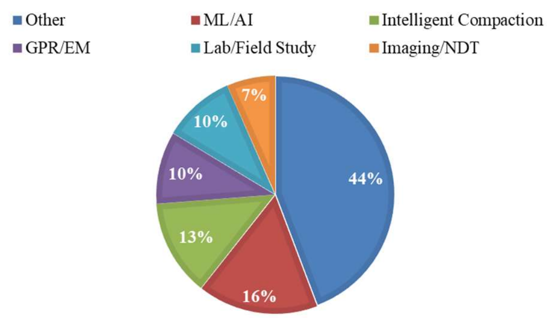

Figure 2. Distribution of Research Approaches Used in Construction Quality Assessment

Figure 2 shows how research methods used in the quality assessment of construction have been distributed, with the major proportion based on traditional and hybrid methods in tandem with emerging intelligent systems. The growing role of machine learning, intelligent compaction and non-destructive imaging methods is indicative of a fundamental move towards data-driven and real-time compaction assessment systems.

Later on, machine learning and data-driven methods have proved to be effective in interpreting the processing of complex sensor data and anticipating soil compaction parameters. The neural networks, gradient boosting, fuzzy systems, and hybrid AI models have been successfully implemented to predict the dry density, moisture content, stiffness, and deformation behaviour. These methods eliminate the need to have large-scale calibration and facilitate real-time decisions within the construction environment. Material informatics and sensor fusion methods also allow a greater predictive capacity by web nonlinear relationships between soil properties and sensor derived variables

New technologies like transmission of wireless signals through soil, quantum sensors, and digital platforms in clouds are broadening the scope of continuous monitoring of the subsurface as well as intelligent management of infrastructure . Taken together, the literature suggests the shift in the destructive point measurements to the integrated, intelligent and automated characterization systems.

In spite of such tremendous gains, there remains a basic trade-off among the current NDT methods. More precise methods including nuclear gauges and gamma-ray tomography are costly and have limited operation capabilities, but fast methods that are low in cost can have lower reliability and calibration sensitivity. Multisensory and AI-assisted systems enhance robustness at the expense of higher complexity and cost of implementation. The constraints show that there is a necessity to have a portable, safe, real-time, and cost-effective non-destructive soil density measurement technique with minimum site-specific calibration factors.

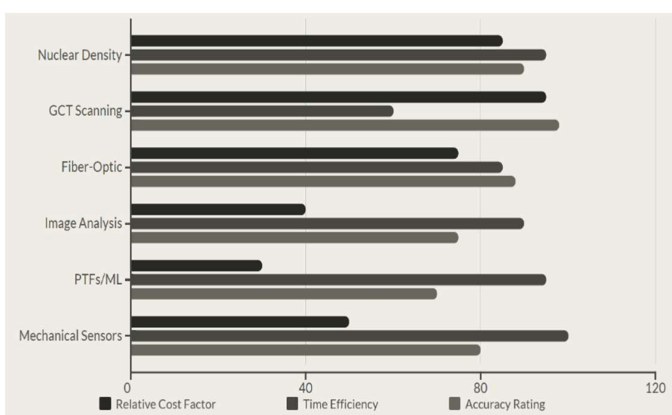

Figure 3. Comparative performance of advanced non-destructive soil density measurement techniques

New penetration techniques of testing soil density using the advanced non-destructive methods of testing (NDT) have been of varying cost, efficiency and accuracy as provided in Figure 4. High-absolution techniques include nuclear density gauges and gamma-ray scanning that are fast and reliable but have a price prohibitive to many, and limitations of health and location. The sensing-based and data-driven approaches, in turn, are more cost-effective and efficient but have average accuracy and calibration-reliance. Generally speaking, the Figure 3 demonstrates a performance-practicality trade-off, which demands a portable, real-time and low-cost solution of the density measurement.

III. EXPERIMENTAL WORK

To examine the behavior of radio wave signals in the soil and to ascertain the relationship between these attributes and the bulk density of soil. One should keep in mind that the properties of incoming electromagnetic waves are dependent on the density of the medium, as well as its physical properties. On getting denser there is a noticeable variation in the signal characteristics of the transmitted signal. Such signal variations can be related quantitatively with laboratory measurements to obtain a soil density value and thus, one can have a non-destructive method of measuring soil density.

The lab equipment was intended to be a design of a radio wave sensing equipment commissioned and a data acquisition unit of microcontroller based microcontroller. The system would be programmed to take and sends radio signals in soil samples sampled and the signal response was recorded. Signal parameters like Received Signal Strength Indicator (RSSI), which are the most important were also measured and stored to be analyzed later, in addition to SNR. The system was calibrated against reference values of bulk density by the use of standard core cutter tests which were conducted in compliance with the IS 2720 (Part 29). This calibration stage was the one that enabled the establishment of stable relation between sensor derived values and the real values of soil density.

In order to make sure that the soil samples had been subjected to realistic variability of fields, soil samples were cultivated under controlled laboratory environment under varying compaction levels, as well as moisture content so that they would be similar to the field. In a test box, the samples were packed in layers to ensure that they had a uniform distribution of the densities. RF transmitter and receiver probes were put on a horizontal plane precisely at the same depth with a high degree of alignment to ensure that there is uniformity in the transmission of signals. Figure 4 shows the overall schematic diagram of the proposed soil density measurement system based on radio waves that shows integrated sensing arrangement that is going to be applied during the experiments.

Different amounts of compaction and moisture content were used to develop laboratory conditions of soil samples of heavy proctor mould size. A test was taken to bring all the specimens in layers to achieve homogeneous density. RF transmitter probe and receiver probe were located horizontally and with the same depth and exact positioning. The overall outline of the proposed radio wave-based system of soil density measurement is depicted in Figure 4 that highlights the joint sensing pattern that is to be examined in the laboratory.

Figure 4. soil density measurement system

Sensitivity of the signal was based on the controlled environmental conditions and various spacing arrangements of the transmitter and receiver probe. The transmission of radio signals into the soil and the subsequent recording of the respective response for each specimen were carried out. Several experiments were conducted with a view to enhancing the repeatability and reliability of the results. The same specimens were tested using core cutters;

that is, they were subjected to standard core cutters to obtain reference values for bulk density, which will be used in the validation process. Throughout the experiment, the temperature and moisture conditions were monitored at all times so that they remain consistent. The output of the sensor parameters and in-lab density values will be the basis for additional statistical and machine learning analyses.

IV. RESULT AND DISCUSSION

The experimental findings of radio wave measurements in the various places and the respective bulk density values computed with the help of the core cutter method. Such differences in the signal reaction at various ground points make it evident that the proposed system is sensitive to changes in soil compaction. The signal characteristics of higher density zones (Location 1) were always stronger than that of lower density ones (Location 2), which proved that the radio wave parameters measured can be largely related to bulk density of soils. The stability of the experimental setup can also be supported by consistency of measurements in repeated positions. These results confirm the prospects of the radio wave-based method as a non-destructive method of estimating soil density.

To first determine the relationship between soil bulk density and sensor-derived parameters, data on the 10cm spacing were first analysed with a multiple linear regression model formulated based on the 10cm spacing data that demonstrated the most consistent performance. The predictive equation resulting between the RSSI and SNR and the density of the soil showed a definite mathematical relationship between the signal and compaction state. The correlation between the predicted and real density is shown in Figure 5 and Figure 6 where the trend analysis and the scatter plot show that there is a strong correlation and that deviation is negligible at all the places of testing.

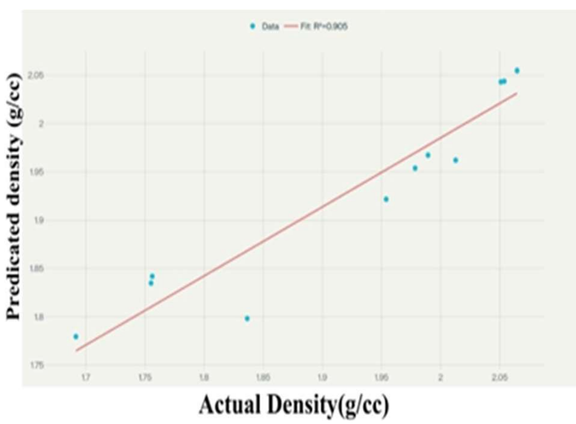

Figure 5. Trend Analysis of predicted density vs actual density (g/cc)

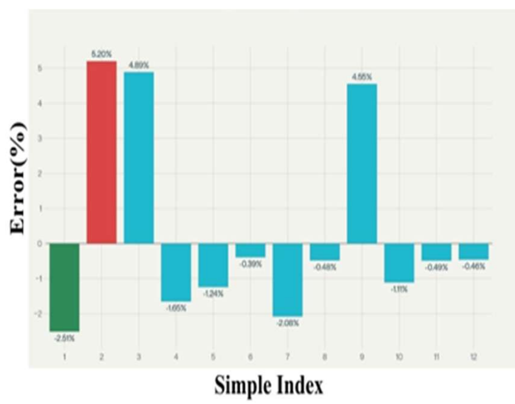

Figure 6. The scatter plot of predicted density vs actual density (g/cc) with the fitted regression line for 10cm spacing

To further examine the predictive performance, machine learning models, including: Random Forest, Support Vector Regression (SVR) and Gradient Boosting were used. Their accuracy measures are summarized in Table I. One of the models that were tested and which seemed to fit the data almost perfectly ($R^2 = 1.0000$) and with very small error values was Gradient Boosting; a second reason why this could have happened is that the dataset is rather small and could thus be easily overfitted.

The predictive power of the random Forest model was also impressive as seen by the R^2 of 0.9046 and low MAE /RMSE, therefore, its ability to generalize is high. On the other hand, the accuracy of SVR is comparatively lower, the R^2 is 0.4215, and the error rates are higher. Additional data that support the high reliability of the Random Forest approach in practice application is derived by visual comparison of the actual and predicted density values of all the models as illustrated in Figure 7.

TABLE I: EVALUATION METRICS FOR ALL MODELS

Metric	Random Forest	SVR	Gradient Boosting
R^2 Score	0.9046	0.4215	1
MAE	0.0308	0.0902	0.0001
MSE	0.0016	0.0099	0
RMSE	0.0404	0.0996	0.0001

Figure 7. Actual versus predicted bulk density for different prediction algorithms   Figure 8. Feature Importance

Figure 8 illustrates the feature importance of the regression analysis machine learning models. On the whole, the findings indicate that sensor based electrical values, especially RSSI, are very sensitive to the changes in soil compaction. A combination of regression analysis with machine learning models allowed the accurate and real-time estimation of the bulk density of the soil with a high correlation to laboratory measurements of core cutter. The proposed method results in a significant saving in time of testing as compared to traditional destructive testing techniques since the proposed method will allow continuous monitoring of the field. These results support the accuracy of the integration of radio wave sensing with data-driven modelling in non-destructive soil characterization.

V. Conclusion

The current paper suggested a machine learning-based radio wave-based non-destructive prediction of the soil bulk density system. Close correlations were also found between the radio signal parameter and the measured bulk density under laboratory validation conditions of experiment. The model that was awarded the best amongst the evaluated algorithms is the Random Forest model with R^2 = 0.9046 and RMSE = 0.0404 g/cc and MAE = 0.0308 g/cc and this implies that the model is a good model with high predictive power and power of generalization. Although the R^2 of Gradient Boosting is 1.000, additional confirmation suggested that there were certain overfitting inclinations due to the limited size of the data. The suggested system is a secure, quick, and economical alternative to the traditional means of destructive testing along with the likelihood of observing real-time compaction. More research should also be conducted in the future in the field validation of the models on large scale and a diverse assortment of soil types and environmental conditions to enhance the effectiveness of the models and their potential usage scenarios

Reference

[1] M. A. Senturk, E. Ordu, and R. K. Tan, Machine Learning -based prediction of soil compaction parameter, Nov. 05, 2024. doi: 10.21203/rs.3.rs-5296226/v1.

[2] Q. Zhao, K. Liu, C. Xiong, X. Deng, and S. Yang, “The estimation of the maximum dry density of soil using least square support vehicle regression individual and hybrid form, Indian Geotechnical Journal, vol. 55, no. 2, pp. 866878, Apr. 2025, doi: 10.1007/s40098-024-00952-3.

[3] K. Kang, J. Lee, H. Park, and J. Lee, Lessening Density Requirement and Density Pay Factors Adjustment of Asphalt Pavements in a Low-quality Sublayer, West Lafayette, Indiana, 2024. doi: 10.5703/1288284317815.

[4] K. Sasaki, H. Aoki, M. Jomoto, and Y. Mori, Application of Road Compaction Quality Control System to Road Pavement Construction to Advanced Quality Control in MAIREINFRA 2023, Basel Switzerland: MDPI, Jul. 2023, p. 47. doi: 10.3390/engproc2023036047.

[5] S.-H. Cheng, S.-S. Chen, and L. Ge, “Method of estimating the effective zone caused by rapid impact compaction, Sci. Rep., vol. 11, no. 1, p. 18336, Sep. 2021, doi: 10.1038/s41598-021-97912-1.

[6] H.-L. Wang and Z.-Y. Yin, “Multi expression programming High performance prediction of soil compaction parameters, Eng. Geol., vol. 276, p. 105758,Oct. 2020,doi: 10.1016/j.enggeo.2020.105758.

[7] F. Tosti, S. Adabi, L. Pajewski, G. Schettini, and A. Benedetto, “Large-scale analysis of dielectric and mechanical properties of pavement using GPR and LFWD,” in Proceedings of the 15th International Conference on Ground Penetrating Radar, IEEE, Jun. 2014, pp. 868–873. doi: 10.1109/ICGPR.2014.6970551.

[8] F. Tosti, S. Adabi, L. Pajewski, G. Schettini, and A. Benedetto, Large-scale analysis of dielectric and mechanical properties of pavement using GPR and LFWD in Proceedings of the 15 th International Conference on Ground Penetrating Radar, IEEE, Jun. 2014, pp. 868873. doi: 10.1109/ICGPR.2014.6970551.

[9] R. Anderegg, D. A. von Felten, and K. Kaufmann, Compaction Monitoring with Intelligent Soil Compactors, in GeoCongress 2006, Reston, VA: American Society of Civil Engineers, Feb. 2006, pp. 1 6. doi: 10.1061/40803(187)41.
[10] M. C. Cavalli et al., "Review of advanced road materials, structures, equipment and detection technologies, Journal of Road Engineering, vol. 3, no. 4, pp. 370-468, Dec. 2023 doi: 10.1016/j.jreng.2023.12.001.
[11] "Optimization of Geotechnical Data Input based on Light weight deflectometer to Road design and performance analysis D. Kuttah, Transportation Infrastructure Geotechnology, vol. 11, no. 6, pp. 37833804, Dec. 2024, doi: 10.1007/s40515-024-00430-6
[12] D. Kuttah, "Optimizing Geotechnical Data Input Based on Light Weight Deflectometer for Road Design and Performance Analysis," Transportation Infrastructure Geotechnology, vol. 11, no. 6, pp. 3783–3804, Dec. 2024, doi: 10.1007/s40515-024-00430-6.
[13] S. Matsumura et al., "3D image scanning of gravel soil using in-situ X-ray computed tomography," Sci. Rep., vol. 13, no. 1, p. 20007, Nov. 2023, doi: 10.1038/s41598-023-46772-y.
[14] M. Barman et al., "Quality control of subgrade soil using intelligent compaction," Innovative Infrastructure Solutions, vol. 1, no. 1, p. 23, Dec. 2016, doi: 10.1007/s41062-016-0020-0.
[15] R. Ranasinghe, A. Sounthararajah, and J. Kodikara, "An Intelligent Compaction Analyzer:Sensors, vol. 23, no. 17, p. 7507, Aug. 2023, doi: 10.3390/s23177507.