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SUMMARY OF REVIEW LITERATURE ON SOIL DATA USING SATELLITE IMAGE AND TECHNIQUES OF ARTIFICIAL INTELLIGENCE

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ABSTRACT:

The current use of remote sensing allows the analysis of soil moisture levels, surface roughness, and texture. These methods help improve our comprehension of soil processes and facilitate informed decision-making, land management, environmental research, soil classification, and more. Currently, artificial intelligence (AI) techniques, such as machine learning (ML) and deep learning (DL), have the potential to be quite impressive in making accurate and efficient predictions for soil texture classification. The use of AI-based methods and techniques for combining data to process satellite imagery and Earth observation data has recently introduced new opportunities for tracking environmental changes and assessment. In this study, we examine a range of recent applications of AI-based methods and techniques for soil data analysis, including regional classification, continuous mapping with automated algorithms, and the optimization (design/re-design) of monitoring networks. Traditional soil classification and analysis methods have many challenges such as time consuming, very high cost, intrusiveness, among others. By accurately measuring the geotechnical properties and characteristics of soil using these methods combined with suitable ML algorithms will lead to different methods and techniques for soil classification. The integration of AI-based approaches in geotechnical engineering will lead to a new direction in risk assessment. The wide range of applications, from forecasting soil failures and landslides to evaluating structural stability, highlights the significant potential of this synergy.

1. INTRODUCTION

Nowadays, satellite images of Earth are captured continuously, serving as essential scientific tools for enhancing environmental understanding and management. These images provide a broad perspective, making it possible to observe large-scale phenomena with a level of accuracy and completeness that would otherwise require a vast network of ground-based observers (Figure 1). A single satellite image can illustrate the spread of air pollution across an entire continent, assess the precise damage caused by earthquakes or wildfires in a specific area, or display the full extent of a 500-km-wide hurricane, from its tranquil eye to its outer storm boundaries (Akhyar et al. 2024).

Figure 1. Earth observation missions
("ESA-Developed Earth Observation Missions," n.d.-a)

Although satellite captures are typically displayed as images, they are fundamentally digital data. This raw data can be processed using specialized software in multiple ways to extract specific information tailored to the needs of each end user. The spatial resolution of Earth observation satellite instruments varies based on their orbit and primary purpose, determining the smallest detectable details in an image (“ESA-Developed Earth Observation Missions,” n.d.-b).

These satellites, which contribute to the advancement of Earth sciences, are instrumental in tackling fundamental scientific inquiries by monitoring and analysing key planetary systems (Dobrynina, n.d.) (Figure 2 and Figure 3).

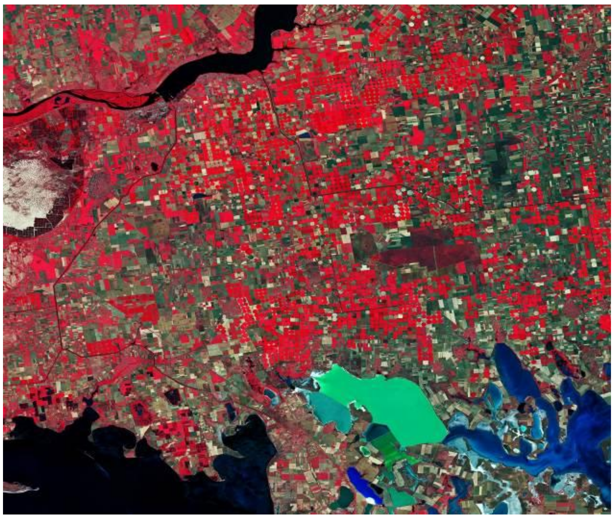

Figure 2. Image captured by the Copernicus Sentinel-2 mission (“View from Above,” n.d.)

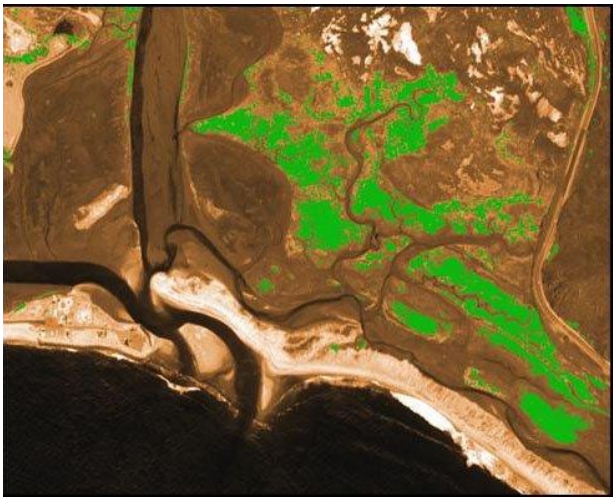

Figure 3. Satellite Image - Soil Index Map (“Soil Zone Index, Agriculture Maps | Satellite Imaging Corp,” n.d.)

The current utilization of satellite-based observation enables the assessment of soil moisture levels, surface irregularities, and composition. These techniques enhance the understanding of soil behavior and support data-driven decision-making in fields such as land management, environmental research, soil classification, and beyond (Abdulraheem et al. 2023).

At present, Artificial Intelligence (AI) techniques, including machine learning (ML) and deep learning (DL), demonstrate considerable potential for generating precise and efficient predictions in soil data classification and analysis (Zhao et al. 2024) (figure 4).

Figure 4. Artificial intelligence techniques: progress, challenges, and perspectives (Zhao et al. 2024)

2. ARTIFICIAL INTELLIGANCE AND METHODOLOGHY

With technology evolving at a fast pace, Artificial Intelligence (AI) has become an increasingly prevalent topic of discussion. The influence of AI spans multiple domains, including virtual assistants, chatbots, autonomous cars, and personalized recommendation systems (Huseynov 2023). At its core, AI involves programming machines to replicate human cognitive functions such as reasoning, learning, and problem-solving. Rather than relying on predefined instructions for specific tasks, AI systems leverage large datasets and advanced algorithms to identify trends, make informed choices, and enhance their efficiency over time. AI encompasses a range of technologies, such as machine learning, natural language processing, robotics, and computer vision, each contributing to its diverse applications (Rashid and Kausik 2024).

Artificial Intelligence (AI) is built on core principles and technologies that empower machines to perform activities that have traditionally required human intelligence. Below are some key concepts (“What Is Artificial Intelligence?” 13:48:44+00:00):

- ***Machine Learning (ML):*** *A method in which algorithms acquire knowledge from data without explicit programming. By training on datasets, these algorithms refine their accuracy over time, allowing them to anticipate outcomes or determine actions when processing new data.*
- ***Neural Networks:*** *Modeled after the human brain, these interconnected algorithms replicate neuron interactions, helping computers recognize patterns and solve AI, machine learning, and deep learning challenges.*
- ***Deep Learning:*** *A subset of AI that utilizes multi-layered neural networks (hence the term “deep”) to analyze data in depth, playing a crucial role in tasks like image and speech recognition.*
- ***Natural Language Processing (NLP):*** *Allows computers to comprehend, analyze, and produce human language, enabling smooth interactions between people and machines.*
- ***Cognitive Computing:*** *Simulates human thought processes to tackle complex problems, often integrating techniques like pattern recognition, NLP, and data mining.*

- ***Expert Systems:*** *Designed to replicate human decision-making by applying logical reasoning to derive conclusions.*

Each of these concepts helps to build systems that can automate, enhance, and sometimes outperform human capabilities in specific tasks. Artificial intelligence (AI) allows machines to learn from data and identify patterns, enabling them to perform tasks more efficiently and accurately. According to (Xu et al. 2021), AI operates in five key steps:

1. ***Input:*** *Data is gathered from multiple sources and categorized accordingly.*
2. ***Processing:*** *AI analyzes the data by identifying patterns it has been trained to recognize.*
3. ***Outcomes:*** *Based on these patterns, AI makes predictions.*
4. ***Adjustments:*** *If an outcome is deemed incorrect, AI learns from the error and refines the process under different conditions.*
5. ***Assessments:*** *Through this continuous cycle, AI constantly improves its accuracy and effectiveness*

These techniques hold great potential for predicting soil properties in geotechnical design (“Artificial Intelligence and Machine Learning Techniques in the Real World of Geotechnical Engineering Practice and Projects,” n.d.). However, they also present challenges, such as assessing an algorithm's performance efficiently and selecting the most suitable one (figure 5).

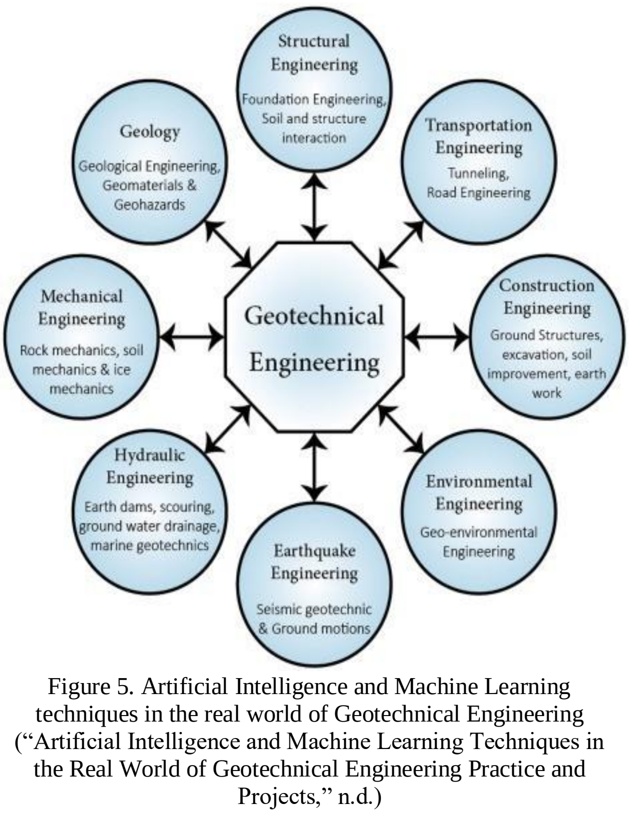

Figure 5. Artificial Intelligence and Machine Learning techniques in the real world of Geotechnical Engineering (“Artificial Intelligence and Machine Learning Techniques in the Real World of Geotechnical Engineering Practice and Projects,” n.d.)

We can say using analytical AI algorithms specialists can analyse the processing and visualisation of soil classification from satellite images.

3. RELATED WORKS

The bibliographic study conducted in this review paper was to inform the scientific sector about the problems that have been resolved so far in the prediction, classification, and visualization of soil from satellite image using techniques from AI. This leads to bibliographic selection by keywords: soil data, satellite images, machine learning, prediction models, geotechnical classification, and published in databases as: IEEE, Springer, Elsevier, Scopus, reasarchgate.net, Web of Science, Crossref, etc. Also, for the selection of the bibliographical articles, we also considered that they should be published in journals, be part of research projects in the research area proposed, and to present best practices from the literature. Articles based only on title and summary without access to all information have been excluded. Based on these criteria we have identified 13 scientific articles that present different problems solved in the field of machine learning for the processing, analysis, and visualization of soil data information (Table 1).

Category	Publications
Representative soil information algorithms of machine learning	Chala, A.T.; Ray, R., Assessing the Performance of Machine Learning Algorithms for Soil Classification Using Cone Penetration Test Data. Appl. Sci. 2023, Mello, D. C. D., Veloso, G. V., Lana, M. G. D., Mello, F. A. D. O., Poppiel, R. R., Cabrero, D. R. O., Di Raimo, L. A. D. L., Schaefer, C. E. G. R., Filho, E. I. F., Leite, E. P., and Demattê, J. A. M.: A new methodological framework for geophysical sensor combinations associated with machine learning algorithms to understand soil attribute 2022, Chala, A.T.; Ray, R., Assessing the Performance of Machine Learning Algorithms for Soil Classification Using Cone Penetration Test Data 2023, Pouyan Pirnia, Francois Duhaime, Mohammad Javad Manashti Machine learning algorithms for applications in geotechnical engineering,
Soil information using images from satellites	Poggio, L., de Sousa, L. M., Batjes, N. H., Heuvelink, G. B. M., Kempen, B., Ribeiro, E., and Rossiter, D.: SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty 2021, Tomislav Hengl, Jorge Mendes de Jesus, Gerard B. M. Heuvelink, Maria Ruiperez Gonzalez, Milan Kilibarda, Aleksandar Blagotić, Wei Shangguan, Marvin N. Wright, Xiaoyuan Geng, Bernhard Bauer-Marschallinger, Mario Antonio Guevara, Rodrigo Vargas, Robert A. MacMillan, Niels H. Batjes, Johan G. B. Leenaars, Eloi Ribeiro, Ichsani Wheeler, Stephan Mantel, Bas Kempen, SoilGrids250m: Global gridded soil information based on machine learning 2017, Piccoli, F.; Barbato, M.P.; Peracchi, M.; Napoletano, P. Estimation of Soil Characteristics from Multispectral Sentinel-3 Imagery and DEM Derivatives Using Machine Learning 2023, Ewing, J., Oommen, T., Jayakumar, P., & Alger, R. Utilizing hyperspectral remote sensing for soil gradation, 2020

Analyse a large soil Data	Kamel H. Rahouma1(&) and Rabab Hamed M. Aly Applying Polynomial Learning for Soil Detection Based on Gabor Wavelet and Teager Kaiser Energy Operator, Alla Yu. Vladova, Time series analysis of geotechnical data from a sensor network controlling the remoted pipeline 2024, Mateja Jemec Auflič, Gerardo Herrera, Rosa Maria Mateos, Eleftheria Poyiadji, Lidia Quental, Bernardie Severine, Tina Peternel, Laszlo Podolszki, Stefano Calcaterra, Arben Kociu, Bartłomiej Warmuz, Jan Jelenek, Kleopas Hadjicharalambous, Gustaf Peterson Becher, Claire Dashwood, Peter Ondrus, Vytautas Minkevičius, Saša Todorović, Jens Jorgen Moller, Jordi Marturia Landslide monitoring techniques in the Geological Surveys of Europe,
Soil strength mapping	Ruizhen Wang, Siyang Wan, Weitao Chen, Xuwen Qin, Guo Zhang, Lizhe Wang, A novel finer soil strength mapping framework based on machine learning and remote sensing images
Literature review for soil classification	P Gopala Raju, M Sowmya, N Chakradhar, R Nithin Kumar, A Review on Soil Classification Using Machine Learning Techniques 2024, Pin Zhang, Zhen-Yu Yin, Yin-Fu Jin, Machine Learning-Based Modelling of Soil Properties for Geotechnical Design: Review, Tool Development and Comparison, Zhang, P., Yin, ZY. & Jin, YF. Machine Learning-Based Modelling of Soil Properties for Geotechnical Design: Review, Tool Development and Comparison

Table 1. Taxonomy and representative publications of Soil data information using techniques of Artificial Intelligence

Several recent studies have demonstrated the applicability of machine learning techniques in soil analysis and mapping using remote sensing imagery and geospatial data. For example, methodological frameworks for soil resilience mapping have been proposed, as well as global soil databases constructed by advanced modelling methods. Other research has explored the spatial uncertainty of these models, the use of geophysical sensors, and the integration of machine learning for estimating soil characteristics. Also, various studies have evaluated the performance of soil classification algorithms based on geotechnical tests and analysed spectral data to determine soil properties (Table 2).

Authors and Title of the papers	**Published**
Ruizhen Wang at all, A novel finer soil strength mapping framework based on machine learning and remote sensing images	Journal Computers & Geosciences Volume 182, January 2024, 105479 https://doi.org/10.1016/j.cageo.2023.105479
Tomislav Hengl at all, SoilGrids250 m: Global gridded soil information based on machine learning	Journal Soil Science February 16, 2017, https://doi.org/10.1371/journal.pone.0169748
Poggio, L., de Sousaat all, SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty	SOIL, 7, 217–240, https://doi.org/10.5194/soil-7-217-2021, 2021.
Mello, D. C. D. at all.: A new methodological framework for geophysical sensor combinations associated with machine learning algorithms to understand soil attributes	Geoscientific Model Development 15, 1219–1246, https://doi.org/10.5194/gmd-15-1219-2022, 2022
Chala, A.T.; at all, Assessing the Performance of Machine Learning Algorithms for Soil Classification Using Cone Penetration Test Data	Applied Sciences, Special Issue The Application of Machine Learning in Geotechnical Engineering, 2023, 13(9), 5758; https://doi.org/10.3390/app13095758
Kamel H. at all, Applying Polynomial Learning for Soil Detection Based on Gabor Wavelet and Teager Kaiser Energy Operator	Springer Nature Switzerland AG 2020A. E. Hassanien et al. (Eds.): AMLTA 2019, AISC 921, pp. 771–783, 2020.https://doi.org/10.1007/978-3-030-14118-9_75
Prof. A V.	Journal of Emerging Technologies and

Deorankar, at all, Soil Health Monitoring System using AI	Innovative Research, ISSN-2349-5162) JETIR1908649
Alla Yu. Vladova, Time series analysis of geotechnical data from a sensor network controlling the remoted pipeline	*Preprints* 2021, 2021040745. https://doi.org/10.20944/preprints202104.0745.v1
Mateja Jemec Auflič, at all, Landslide monitoring techniques in the Geological Surveys of Europe	Springer, LANSLIDE, Published: 03 January 2023, Volume 20, pages 951–965, (2023) https://doi.org/10.1007/s10346-022-02007-1
Pin Zhang, at all, Machine Learning-Based Modelling of Soil Properties for Geotechnical Design: Review, Tool Development and Comparison	Springer, Archives of Computational Methods in Engineering, Published: 05July2021, Volume 29, pages 1229–1245, (2022), https://doi.org/10.1007/s11831-021-09615-5
Piccoli, F.; at all, Estimation of Soil Characteristics from Multispectral Sentinel-3 Imagery and DEM Derivatives Using Machine Learning	Journal Sensors, Issue Intelligent Agricultural Applications with Sensing and Vision System, 2023, https://doi.org/10.3390/s23187876
Aydın, Y.; at all, Use of Machine Learning Techniques in Soil Classification	Journal Sustainability, Issue Machine Learning Applications in Civil Engineering for Sustainability, 2023, https://doi.org/10.3390/su15032374
Ewing J., at all, Utilizing hyperspectral remote sensing for soil gradation	Journal Remote Sensing, VNIR-SWIR Spectroscopic and Remote Sensing Applications to Earth Science and Environmental Issues, 2020; https://doi.org/10.3390/rs12203312

Table 2. Relevant articles for analysing soil data using satellite image and AI techniques

All these works contribute significantly to the understanding and improvement of modern soil analysis techniques.

4. DISCUSSIONS

Soil classification is an essential field in multiple areas of research, and modern remote sensing and machine learning methods have significantly improved the accuracy and applicability of these classifications. In this comprehensive bibliographic research, authors highlight the use of advanced methods, such as remote sensing, machine learning, and geophysical analysis, to improve the accuracy and efficiency of soil classification.

For agriculture, platforms such as SoilGrids and hyperspectral remote sensing techniques enable detailed soil mapping and fertility assessment. Hengl et al. provide global-scale digital mapping using machine learning and remote sensing data, with the advantage of global coverage and wide accessibility. However, its resolution is limited to 250 m. On the contrary, Mello et al. significantly improves prediction accuracy by using Sentinel-3 multispectral imagery and DEM models, increasing the accuracy of the estimates by up to 65%, being more effective for soil texture and cation exchange capacity (CEC) (Figure 6).

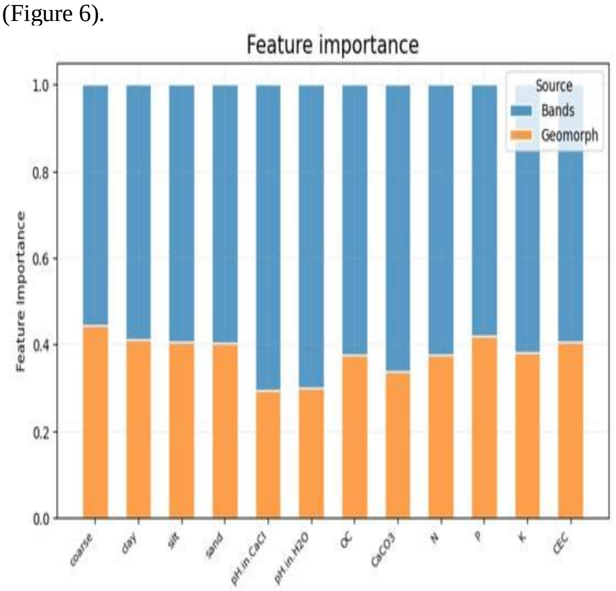

Figure 6. Aggregated feature importance of each soil variable. The contributions of the multispectral and geomorphological DEM derivatives are shown in blue and orange, respectively. It is worth noting that the importance of the multispectral variables is greater than that of the DEM derivatives (Mello et al. 2022)

On the other hand, Ewing et al. adds an innovative approach through hyperspectral remote sensing, providing a non-invasive alternative to traditional analysis methods, more accurate for characterization of sand, clay and gravel (figure 7).

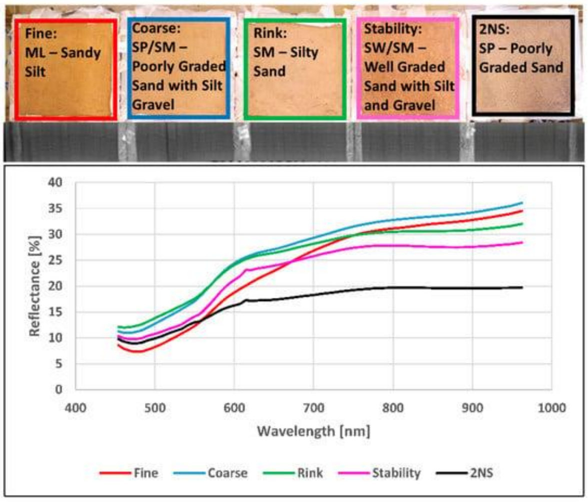

Figure 7. Shows the hyperspectral plot for each soil. Each colored box and the corresponding line are different soil types. Going from left to right: Fine, Coarse, Rink, Stability, and 2NS (Ewing et al. 2020)

Integration of Sentinel-3 multispectral imagery and digital elevation models (DEMs) improves terrain modelling and identification of paedogenetic processes for geomorphological soil classification. Piccoli et al. apply ML combined with Sentinel-3 and DEM data to improve geomorphological mapping, enabling the identification of complex patterns of large-scale land evolution. Deorankar and Rohankar adopt an approach based on ML classification of soil imagery, providing a fast and efficient method for terrain assessment without the need for laboratory analysis, reducing costs and processing time. In comparison, Rahouma and Aly use neural networks to analyse soil texture and structure, being more accurate in identifying erosion-prone areas and geomorphological stability (Figure 8).

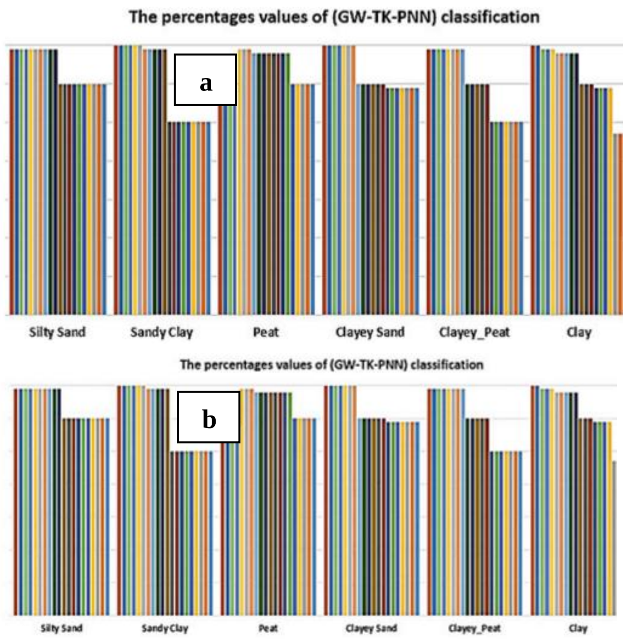

Figure 8. The result of a) GW-multi-SVM of the previous research (energy) and b) applying-Gabor wavelet—TK-PNN (energy) (Rahouma and Aly 2020)

Classification methods based on the Unified Soil Classification System (USCS) combined with machine learning algorithms and cone penetration testing (CPT) provide an accurate estimation of its mechanical properties that are essential for foundation design and stability of structures essential to the field of geotechnical engineering. Wang et al. use ML for USCS classification, allowing fast and accurate soil identification without the need for laboratory tests, thus reducing geotechnical costs. On the contrary, Chala and Ray combine CPT tests with ML (SVM, RF, ANN), achieving up to 99.8% accuracy and being extremely useful in analysing soil behaviour for foundations (Figure 9).

a

ML Models	Soil Type	Sensitivity	Precision	F1_Score
ANN	2	0.96	0.99	0.98
	3	0.96	0.97	0.96
	4	0.99	0.99	0.99
	5	0.99	0.99	0.99
	6	0.98	0.97	0.98
	7	0.67	0.91	0.77
RF	2	1	0.99	0.99
	3	1	0.99	0.99
	4	1	0.99	0.99
	5	1	0.99	0.99
	6	1	0.99	0.99
	7	0.98	0.96	0.97
SVM	2	1	1	1
	3	1	1	1
	4	1	1	1
	5	1	1	1
	6	0.99	1	0.99
	7	0.97	0.93	0.95
DT	2	0.98	0.95	0.96
	3	0.93	0.96	0.95
	4	0.96	0.95	0.96
	5	0.96	0.96	0.96
	6	0.93	0.94	0.94
	7	0.94	0.83	0.88

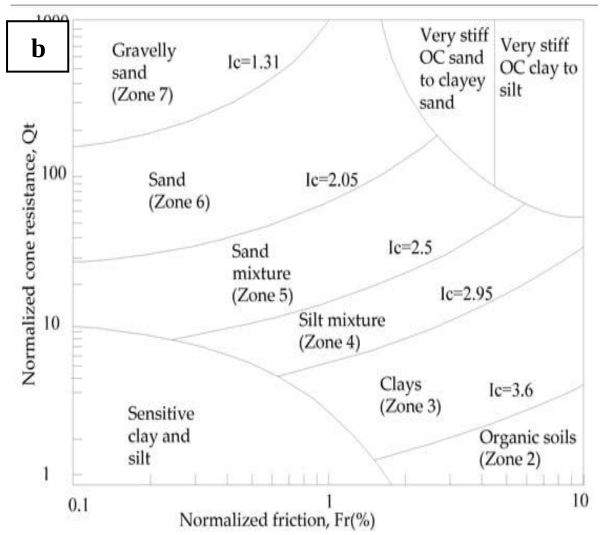

Figure 9. a) Performance metrics of ML models for each soil type and b) Robertson soil classification chart based on soil behavioral type index, Ic (Chala and Ray 2023)

Zhang et al. apply maximum dry soil density modelling, being a crucial method for soil compaction and optimization of geotechnical projects. The use of Cone Rating Index (RCI), soil temperature monitoring and landslide analysis contribute to the assessment of ground stability and sustainable infrastructure design, essential in civil engineering. Wang et al. use the RCI index and USCS rating for soil strength analysis, providing critical information for mobility and construction (Figure 10).

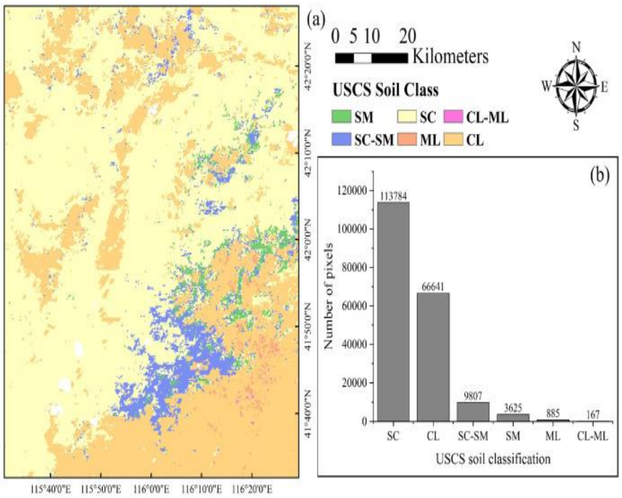

Figure 10. (a) Prediction of USCS soil classification based on SoilGrids (white regions are no data region including water and architecture) and (b) statistics of pixels in the study site of Shandian River Basin (Wang et al. 2024)

Alla Yu. propose a model for monitoring soil temperature in areas with underground pipelines, vital for preventing structural changes caused by temperature variations. On the contrary, Auflič et al. apply ML and remote sensing for landslide monitoring, contributing to early warning and geotechnical risk reduction.

The results of the bibliographic research suggest that for agriculture and geomorphology, the integration of SoilGrids, Sentinel-3, and machine learning algorithm technologies provides high precision in soil property estimation, facilitating the practical applicability of these methods in land mapping and monitoring.

With respect to geotechnics and civil engineering, the combined use of machine learning (ML), RCI index, cone penetration testing (CPT) and USCS classification constitutes an optimal approach for the evaluation of geotechnical soil characteristics. This methodology contributes significantly to the design of reliable and safe structures by providing a more detailed and predictive characterisation of soil stability.

The implementation of these advanced technologies not only improves the accuracy of soil classification, but also reduces the cost and time associated with conventional analysis. Therefore, these methods are proving to be essential tools for researchers and specialists in the fields of pedology, geomorphology, geotechnics, and civil engineering, having a significant impact on optimising decision-making processes and sustainable land management.

5. CONCLUSIONS

AI techniques have proven to be highly versatile, efficient, and nonlinear tools, widely applied in geological and environmental studies. Their effectiveness spans all stages of environmental data mining, from exploratory spatial data analysis to detecting and modelling spatial-temporal patterns and generating decision-oriented maps. Recent advancements in AI applications for geotechnics and civil engineering emphasize key aspects such as advanced dimensionality reduction, spatial data visualization, and the rapid simulation of physical processes within hybrid models. Additionally, AI-driven methods facilitate the extraction, modelling, and prediction of complex spatial-temporal structures, enhancing the accuracy of data analysis and interpretation.

However, as these techniques rely on data-driven models, their successful implementation requires a deep understanding of both AI methodologies and domain-specific knowledge. Future research should focus on refining AI applications, optimizing data integration strategies, and expanding their practical use in geotechnical risk assessment and infrastructure stability, ensuring more reliable and sustainable engineering solutions.

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