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Review Article

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Rs & Gis In Geotechnical Engineering: A Comprehensive Overview and Applications

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Abstract

The integration of Remote Sensing (RS) and Geographic Information Systems (GIS) has emerged as a powerful approach in the field of geotechnical engineering. This comprehensive report explores the diverse applications of RS and GIS technologies in geotechnical engineering, focusing on their roles in site investigation, hazard assessment, and infrastructure design. The report delves into the use of RS data, including satellite imagery, aerial photographs, and LiDAR, to gather critical geospatial information for geological mapping and terrain analysis. It elucidates how GIS aids in data integration and visualization, providing a holistic understanding of subsurface conditions, geological structures, and geohazards.

The report further highlights the applications of RS and GIS in slope stability analysis, landslide monitoring, and foundation design. In addition, it addresses the significance of RS and GIS in environmental impact assessments, groundwater management, and infrastructure asset management within the geotechnical context. The findings presented in this report underscore the transformative potential of RS and GIS technologies, offering geotechnical engineers a comprehensive toolkit to make data-driven decisions, enhance safety, and optimize the planning and design of geotechnical projects. As the field of geotechnical engineering continues to evolve, the integration of RS and GIS is poised to play an increasingly pivotal role in shaping sustainable and resilient infrastructures in the face of complex geological challenges.

Keywords: Remote Sensing (RS), Geographic Information Systems (GIS), Geotechnical Engineering, innovative applications

Abbreviations:

RS : Remote sensing
GIS : Geographical Information System
QGIS : Quantum Geographical Info. System
MCDA : Multi-criteria decision analysis
LiDAR : Light Detection and Ranging
InSAR : Interferometric Synthetic Aperture Radar
DEM : Digital elevation models
InSAR : Interferometric Synthetic Aperture Radar
ESRI : Environmental Systems Research Institute
SPT : Standard Penetration Test
CPT : Cone Penetration Test
DEM : Digital Elevation Model

1. Introduction

Geotechnical engineering involves the study of the behavior and properties of soils and rocks to understand their suitability for construction projects. Remote Sensing (RS) and Geographic Information Systems (GIS) have emerged as powerful tools that can enhance geotechnical investigations and provide valuable insights for engineering applications. This report explores the various applications of RS and GIS in geotechnical engineering, highlighting their benefits and impact on the field.

2. Overview of Rs And Gis:

2.1 Remote Sensing:

Remote Sensing refers to the collection of data about the Earth's surface from a distance, typically using aerial or satellite imagery. RS techniques involve the capture, analysis, and interpretation of data related to topography, land cover, vegetation, and surface conditions.

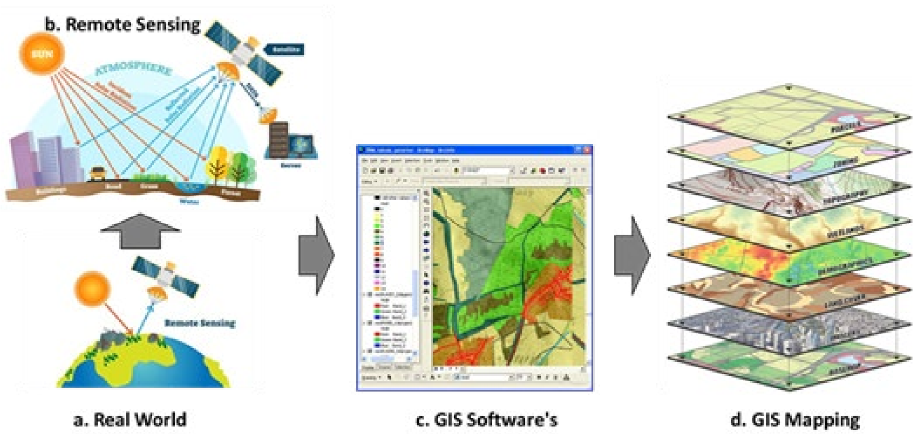


Figure-1: Working principle of RS & GIS

2.2 Geographic Information Systems:

Geographic Information Systems are computer-based systems used for the capture, storage, manipulation, analysis, and visualization of spatial data. GIS integrates various data sources, including RS imagery, topographic maps, and geospatial data, to facilitate spatial analysis and decision-making. Table- 3 (Appendix), deliberates various GIS software's along with its main advantages and limitations.

2.3 Review of literature:

Federal Highway Administration –FHWA (2002) published a report on RS and GIS applications in geotechnical engineering in which soil boring management systems deliberated exclusively using GIS software NJ DOT. Soil attributes such as depth, Horizons of soil types, soil particle size distribution, plasticity index, etc. were studied exclusively. Priya S. (2003) delineated applicability of various software application in combination of GIS tools such as Borehole Viewer and Strip chat. Roger J and Luna R (2004) described sequence of origin of RS and GIS over three decades starting from 1970. Types of sensors, common inputs, data processing, analytical methods applicable to GIS and challenges of using GIS representation of geotechnical data was discussed exclusively by different respective case studies. Esaki T et al. (2006) introduced advance application of GIS technology to rock engineering. He discussed the future perspective of GIS application to rock engineering, considering the data collection, data analysis, coupling of GISs with the various analysis tools and modules.

Gandhimathi A. (2010) developed SCPM model (Soil characteristic prediction model) for the prediction of soil parameters required for foundation design. The values predicted using the designed model were found to have close agreement with the actual values in field. Rosen J.B. (2011) applied GIS technology to acquire information from multiple data source and created decision making model) using geotechnical feedback to handle quality control in project management data for cut-off wall construction project.

2.4 Mapping requirement in Geotechnical Engineering

Geotechnical engineering requires various types of maps to facilitate the practice and decision-making processes. These maps provide valuable spatial information about the geological and geotechnical properties of an area. Here are some essential types of maps used in geotechnical engineering:

Geological Maps: Geological maps display the distribution and characteristics of different rock formations and soil types in a given region. They provide information about the geological history, stratigraphy, and structural features of the area, which are crucial for understanding the behavior of subsurface materials.

Topographic Maps: Topographic maps depict the elevation and contour lines of the land surface. They help in identifying the topographic features such as hills, valleys, ridges, and slopes, which are important considerations in geotechnical site investigations and construction planning. (figure-3)

Geophysical Maps: Geophysical maps show the subsurface properties of an area, such as variations in rock density, electrical resistivity, and seismic velocities. Geophysical surveys help to detect hidden structures, groundwater levels, and potential geotechnical hazards like faults or voids.

Borehole Logs: Borehole logs are vertical representations of subsurface soil and rock layers obtained from drilling exploratory boreholes. These logs present detailed information about the soil and rock types, their depth, strength, and other geotechnical parameters.

Soil Maps: Soil maps specifically focus on the distribution of different soil types within a region. They provide valuable information about soil properties, such as grain size, permeability, bearing capacity, and shear strength, which are essential for foundation design and construction.

Landslide Susceptibility Maps: Landslide susceptibility maps identify areas prone to landslides based on factors like slope angle, geology, and historical landslide events. These maps aid in planning and mitigating landslide risks for infrastructure projects.

Seismic Hazard Maps: Seismic hazard maps illustrate the potential for earthquake-induced ground shaking in a region. These maps are crucial for designing earthquake-resistant structures and assessing seismic risks.

Groundwater Maps: Groundwater maps show the distribution and depth of the water table and provide insights into the regional groundwater flow patterns. Understanding groundwater conditions is essential for foundation design and excavation projects.

Environmental Maps: Environmental maps can include information about potential contamination sources, wetlands, wildlife habitats, and other ecological factors that might impact geotechnical projects.

Infrastructure and Utilities Maps: These maps show the location of existing infrastructure, utilities, and underground services. Knowing the location of these features is crucial to avoid conflicts during construction.

By utilizing these different types of maps, geotechnical engineers can gain a comprehensive understanding of the subsurface conditions and make informed decisions during the planning, design, and construction stages of various civil engineering projects.

3. Applications of Rs And Gis In Geotechnical Engineering:

3.1 Site Selection and Investigation:

RS and GIS techniques enable geotechnical engineers to analyze vast amounts of spatial data, aiding in site selection for infrastructure projects. Satellite imagery and terrain models provide valuable information on topography, geology, and land cover, helping identify potential geotechnical hazards and determining suitable construction locations.

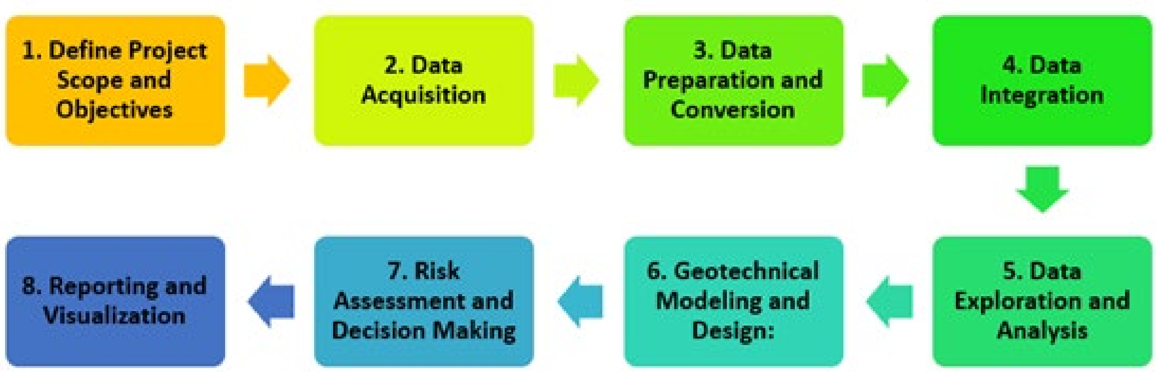


Figure-2: Applicability and sequence of operation for Geographic Information system incorporated in Geotechnical Engineering

The flow char (figure-2) describes the sequence of operations to handle any geotechnical project along with RS and GIS interface.RS becomes useful in step-2 for data acquisition and GIS technology can be exclusively applicable from step 3 to step-7. Here only step-6 may require purely geotechnical software's for analysis and design of geotechnical structures. GIS software's can generate tables, maps (in 2D & 3D), which enhances the reporting and visualization information.

GIS for generating maps of geotechnical properties such as SPT N value, bearing capacity, soil classification, shear parameters of soil, ground water table, GIS for contour and elevation map.

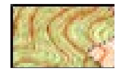
Legends in GIS map	
	Glaciers
	Rock areas
	Forests

Figure-3 A 1:100k Soviet army map shows the Chobia pass trail across the Pir Panjal range, an ancient shepherd migration route from Chamba to Lahaul, India.

Image source: https://ultrajourneys.org/mapping-the-western-himalaya/

GIS for interpolating missing data- GIS (Geographic Information Systems) can be a valuable tool for interpolating missing geotechnical data in various geotechnical engineering and environmental applications. Interpolating missing data refers to the process of estimating values at specific locations based on the values available at nearby known locations.

The accuracy of the interpolation heavily depends on the spatial distribution of the available data and the interpolation method chosen. The reliability of the results should be carefully assessed, and caution should be exercised when making critical decisions based on the interpolated data, especially in regions with limited or sparse data coverage. However, whenever possible, collecting more geotechnical data at specific locations is the best approach to improve the accuracy of the analysis.

3.2. Foundation design and post construction behavior

3.3 Geo-Hazard analysis and management

Geo-hazards are natural or human-induced events and processes that pose risks to human life, property, and the environment due to geological factors. Landslides, Earthquakes, Volcanic Hazards, Sinkholes, Subsidence, Coastal Erosion, Rock falls and Rockslides, Debris Flows and Mudslides, Permafrost Thawing, Ground Heave and Swelling Soils, Seepage and Piping, Submarine Landslides and Karst Hazards are geotechnical hazards.

I. Slope Stability Analysis with RS and GIS:

RS and GIS are essential for assessing slope stability. By integrating topographic, land cover, and geological data, engineers identify unstable slopes, potential landslide areas, and analyze factors contributing to slope failures, aiding in designing stabilization measures.

Applications of RS and GIS in Slope Stability:

i. Terrain Mapping: RS generates accurate DEMs and GIS analyzes slope characteristics, identifying instability-prone areas for mapping high-risk zones.

ii. Landslide Detection: RS techniques like image classification and InSAR monitor landslides, helping create inventory maps and assess susceptibility.

iii. Slope Stability Modeling: RS and field data combined with GIS-based models evaluate slope stability and failure mechanisms, aiding decision-making.

iv. Hazard Zonation and Risk Assessment: RS and GIS create hazard zonation maps based on factors like slope angle and geology, facilitating risk assessment.

v. Emergency Response and Planning: RS data quickly assesses slope failures, aiding emergency responders in prioritizing actions and planning evacuations.

vi. Long-term Monitoring: RS and GIS monitor slope movements, erosion, and vegetation changes over time, informing maintenance and mitigation strategies.

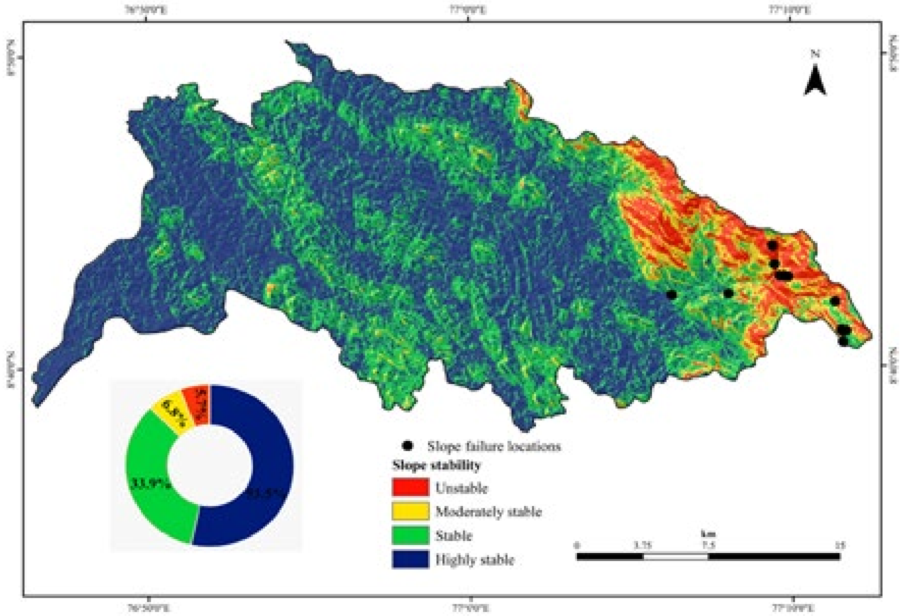


Figure-4: The predicted slope stability map of Vamanapuram River Basin, Kerala, South India.

(After C.D. Aju et al 2021)

The combination of RS and GIS aided by software tools generates slope stability maps classified as unstable, moderately stable, and stable and highly stable slopes. Figure – depicts slope stability map for the Vamanapuram river basin of Kerala state of South India region. Such maps help geotechnical engineer prior to the reconnaissance survey.

II. RS and GIS are vital for monitoring land subsidence.

RS techniques like satellite imagery, aerial photography, and LiDAR provide high-resolution data, detecting changes in land elevation over time. InSAR measures surface deformations with precision, identifying even small-scale subsidence. GIS creates and manages subsidence monitoring networks, integrating RS, ground-based, and geological data. Time-series analysis in GIS tracks subsidence rates and trends using multi-temporal satellite imagery. GIS-based spatial analysis assesses subsidence risk by combining geological, groundwater, and historical data. Managing groundwater levels in GIS helps understand the relationship with subsidence. GIS facilitates vulnerability mapping, identifying at-risk areas and infrastructure. Decision support systems in GIS aid stakeholders in subsidence data interpretation, informing land use, infrastructure, and groundwater management strategies. The integration of RS and GIS technologies in land subsidence monitoring enhances the understanding, assessment, and management of subsidence phenomena. These tools enable the identification of subsidence patterns, detection of small-scale deformations, monitoring of groundwater levels, vulnerability mapping, and the development of decision support systems for effective land subsidence management. Figure-5 below depicts the steps to be followed to generate land subsidence susceptibility maps and its validation by test data. It is peculiar that in to the software tools it is possible to vary conditioning factors as per the ground situations.

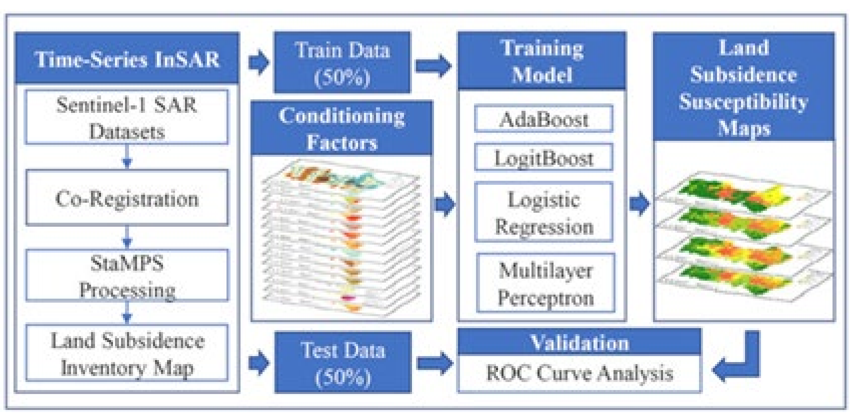


Figure-5: Land Subsidence Susceptibility Mapping Using Functional and Meta-Ensemble Machine Learning Algorithm Based on Time-Series InSAR Data. (After Hakim WL et al (2020)

RS techniques, such as Interferometric Synthetic Aperture Radar (InSAR), provide a means to monitor land subsidence, which is a critical geotechnical concern. InSAR measures ground surface displacements over time, helping identify areas prone to subsidence due to geological factors or human activities like groundwater extraction or mining.

III. Earthquake and Seismic Hazard Assessment:

GIS can be utilized to map seismic activity and assess earthquake hazards in a region. By integrating geological and seismological data, engineers can better understand the potential impact of earthquakes on infrastructure and plan accordingly.

Liquefaction potential and seismic micro-zonation are two critical aspects of seismic hazard assessment, especially in regions prone to earthquakes. They play a significant role in understanding the potential impact of seismic events on the built environment and infrastructure. Here's a brief explanation of each:

Liquefaction Potential: Liquefaction is a phenomenon that occurs during certain seismic events when loose, saturated soils lose their strength and behave like a liquid. It can lead to significant ground shaking and cause severe damage to buildings, bridges, and other structures. Assessing the liquefaction potential is crucial to understanding the vulnerability of a site to liquefaction-induced hazards.

Methods for liquefaction potential assessment often involve evaluating soil characteristics, such as grain size distribution, fines content, and groundwater levels. Standard penetration tests (SPT), cone penetration tests (CPT), and shear wave velocity measurements are commonly used to determine soil properties. By integrating this geotechnical data with seismic hazard information, geologists and engineers can estimate the likelihood of liquefaction during earthquakes.

Seismic Micro-zonation: Seismic micro-zonation involves subdividing a region into smaller zones based on variations in geological and geotechnical properties. The aim is to create detailed maps that depict the variability of seismic ground motion and hazard levels across the area.

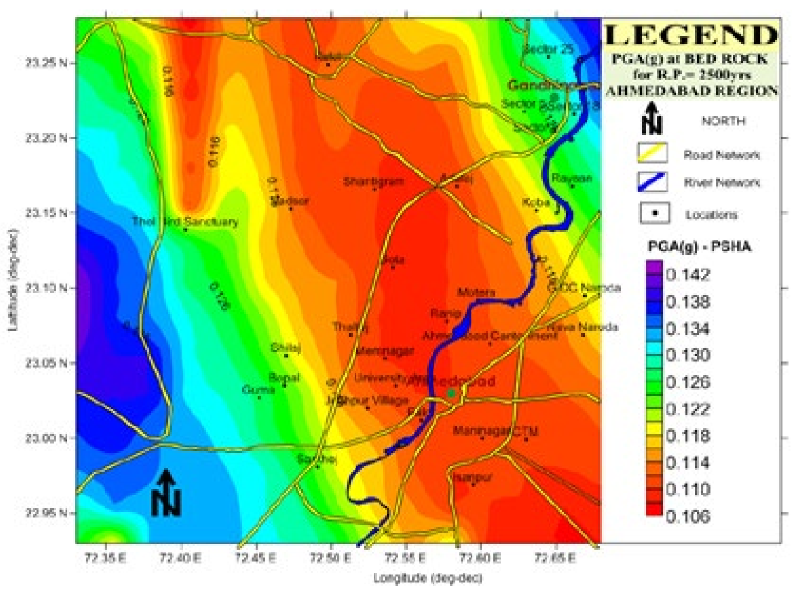


Figure-6: Seismic micro zonation (after- Bhandari T. and Thaker T.P. (2020))

To perform seismic micro-zonation, geologists and geotechnical engineers use various data sources, including geological maps, soil surveys, and seismic data. They may also consider historical seismicity and fault line distribution. By considering these factors, the region is categorized into zones with different seismic hazard levels, indicating areas of high, moderate, and low seismic risk.

Seismic micro-zonation provides critical information for land-use planning, infrastructure development, and disaster preparedness. It helps policymakers, engineers, and urban planners to make informed decisions on where to locate critical infrastructure, identify areas requiring special seismic design considerations, and develop appropriate mitigation measures. Figure-6 shows the seismic micro zonation of Ahmedabad city along with river Sabarmati, major roads and wards of Ahmedabad city.

Both liquefaction potential assessment and seismic micro-zonation are essential components of seismic hazard assessment. Understanding the potential for liquefaction and the spatial distribution of seismic hazards allows for better risk mitigation strategies and the development of earthquake-resistant infrastructure to protect communities and assets in earthquake-prone regions.

Seismic micro zonation and seismic zonation are crucial concepts in earthquake risk assessment and preparedness in India.

Seismic Zonation in India:

Seismic zonation refers to the division of a region or country into different seismic zones based on the level of seismic activity and the potential for earthquakes. In India, seismic zonation is essential for understanding earthquake risk and designing buildings and infrastructure that can withstand seismic forces. The Bureau of Indian Standards (BIS) has classified India into four seismic zones, namely Zone II, Zone III, Zone IV, and Zone V, with Zone V being the most seismically active. These zones help in determining the seismic design parameters for construction projects and the earthquake-resistant measures that need to be implemented.

Seismic Micro zonation in India:

Seismic micro zonation takes the concept of seismic zonation to a more detailed level by studying specific localities or regions within a seismic zone. It involves the mapping of the ground's response to seismic waves, which can vary significantly even within the same seismic zone. Seismic micro zonation studies aim to identify areas with higher vulnerability to ground shaking, liquefaction, landslides, and other seismic hazards. These studies consider geological, geotechnical, and geophysical factors to create detailed hazard maps for urban planning and disaster management. India has conducted seismic micro zonation studies in various cities, such as Delhi, Mumbai, and Chennai, to assess the earthquake risk at a local level and inform construction practices and disaster preparedness. Table-2 (Appendix) shows chronological efforts made in the field of seismic micro zonation for various cities of India as well as pan India seismic zonation.

IV. Geohazard Mapping:

RS and GIS technologies aid in geohazard mapping by analyzing various factors like terrain, land cover, seismic data, and historical landslide occurrences. These tools assist in identifying areas prone to earthquakes, landslides, or other geological hazards. Geohazard maps guide land-use planning, infrastructure design, and disaster mitigation strategies.

Geohazard mapping using Remote Sensing (RS) and Geographic Information Systems (GIS) involves the integration and analysis of various spatial data to identify areas prone to natural hazards. Here is a step-by-step guide on how to perform geohazard mapping using RS and GIS:

Geohazard mapping with RS and GIS involves analyzing terrain, land cover, seismic data, and historical landslides to identify hazard-prone areas. Follow these steps:
i. Define Study Area: Determine the geographic extent for mapping.
ii. Gather Data: Acquire relevant RS and spatial datasets.
iii. Preprocess Data: Correct distortions and align datasets in GIS.
iv. Extract Geohazard Indicators: Derive hazard-related parameters from RS data.
v. Analyze Indicators: Use GIS tools for spatial analysis and pattern recognition.
vi. Weight and Rank Indicators: Assign significance to indicators and combine them for hazard susceptibility or risk mapping.
vii. Validate Results: Verify mapping accuracy using ground truth data and expert knowledge.
viii. Generate Geohazard Maps: Create visual maps indicating susceptibility levels.
ix. Interpret and Communicate: Explain findings clearly to stakeholders and the public.
x. Update and Maintain: Regularly refresh maps with new data for accuracy and relevance. Collaborate with experts and conduct field verification for reliable mapping.

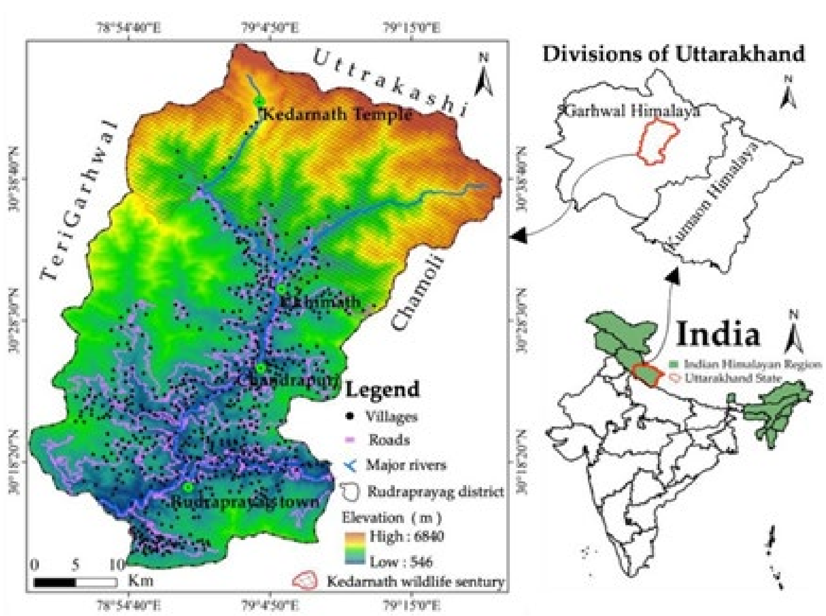


Figure-7: (After- [3] Batar, A.K.;Watanabe, T. 2021)

Geo hazard map of Rudra Prayag of Uttarakhand, India shown in figure- depicts the high to low susceptibility of geo-hazard along with villages, roads, major rivers and its tributaries. The information available after GIS inclusion guides geotechnical engineers to correlate the variation of geotechnical properties or behavior of soil with respect to elevation, ground water conditions and presence of waterbodies.

3.4 Groundwater Management:

GIS-based hydrological modeling with RS data aids groundwater resource assessment and management. Integrating rainfall, land use, hydrological, and geological data enables modeling of groundwater flow, aquifer evaluation, and optimized water resource planning. Following are some applications of RS & GIS in ground water management.

i. Groundwater Data Integration: RS provides land surface data, while GIS combines diverse sources for comprehensive analysis.

ii. Aquifer Mapping: RS and GIS create aquifer maps, characterizing extent, properties, and vulnerability zones.

iii. Groundwater Monitoring: RS-based measurements track regional groundwater changes, complemented by GIS analysis of well data.

iv. Water Balance Estimation: RS data, integrated into GIS, calculates water balance components and recharge rates.

v. Vulnerability Assessment: GIS integrates spatial data to assess contamination risk and overexploitation, guiding resource protection.

vi. Decision Support Systems: GIS-based systems offer tools for informed decision-making, including modeling and scenario analysis.

vii. Public Awareness: RS and GIS tools develop interactive platforms, promoting groundwater importance and sustainable water use. RS and GIS technologies offer powerful capabilities for groundwater management. They enable the acquisition and integration of data, aquifer mapping, groundwater monitoring, water balance estimation, vulnerability assessment, decision support systems, and public education. By utilizing these tools, stakeholders can make informed decisions, optimize resource allocation, and work towards sustainable groundwater management practices.

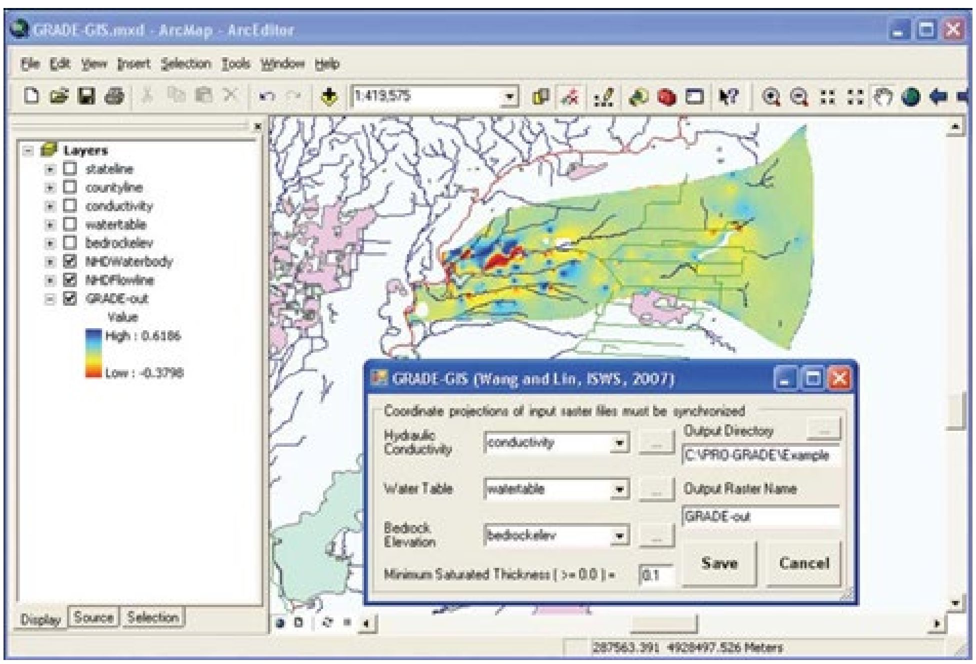


Figure-8: The graphical user interface of GRADE-GIS and the estimate recharge and discharge map of Buena Vista Groundwater Basin, Wisconsin, comparing surface water features in ArcMap (https://www.esri.com/news/arcuser/0408/groundwater.html)

Figure- shows the software interface (ArcGIS) for ground water modelling where the layers of ground water map can be fused with bedrock depth, bedrock type, river basin, hydraulic conductivity of rocks etc. as per the requirement of geotechnical analyst.

3.7. Construction and Excavation Planning: GIS provides valuable support in planning construction and excavation projects by offering a range of capabilities. Engineers can effectively visualize the project area in GIS, gaining a comprehensive understanding of the terrain and surrounding features. By integrating geological and geotechnical data, they can identify potential risks such as unstable ground, slope instability, or areas prone to flooding. GIS allows engineers to analyze these risk factors spatially, enabling them to make informed decisions and implement appropriate mitigation strategies.

Furthermore, GIS assists in optimizing the layout and alignment of structures within the project area. By overlaying various datasets, including soil types, land use, and infrastructure, engineers can identify the most suitable locations for buildings, roads, and other structures. This data-driven approach helps minimize the impact on the environment and surrounding communities while maximizing the efficiency and safety of the project.

Overall, GIS serves as a powerful tool for construction and excavation planning, ensuring that projects are well-informed, environmentally conscious, and optimized for success. Its ability to visualize and analyze complex spatial data enables engineers to make data-driven decisions that lead to well-planned and sustainable infrastructure development.

3.8 Application in rock engineering: Remote Sensing (RS) and Geographic Information Systems (GIS) have various applications in rock engineering, enhancing understanding, analysis, and decision-making in this field. Some of the applications of RS & GIS in rock engineering are rock mass characterization, rock slope stability analysis, rock fall hazard assessment, rock mass classification, geological mapping, rock mass monitoring, rock slope design, rock blasting planning and rock mass modelling and 3D visualization. RS and GIS applications in rock engineering contribute to better understanding, planning, and management of rock-related projects. They improve safety, efficiency, and decision-making, ultimately leading to more successful and sustainable rock engineering endeavors.

3.9. Land reclamation and ground improvement: RS and GIS are valuable for land reclamation projects, aiding in planning, monitoring, and assessment. Applications include site assessment, selection analysis, baseline data collection, vegetation monitoring, and environmental impact assessment. Hydrological modeling, slope stability analysis, and land cover mapping support effective reclamation strategies. GIS facilitates erosion control, community engagement, and decision-making. These technologies promote sustainable and ecologically sensitive reclamation practices, restoring disturbed lands for various beneficial purposes.

3.10. Environmental Impact Assessment: GIS plays a crucial role in conducting comprehensive environmental impact assessments (EIAs) by offering essential spatial data related to various factors impacted by construction activities. Through GIS, professionals can access information on soil erosion, soil contamination, habitat mapping, and other crucial environmental elements. This data aids in understanding the potential environmental consequences of construction projects, enabling better decision-making and planning to minimize negative impacts and promote sustainable development practices.

4. Advantages of RS and GIS in Geotechnical Engineering:

4.1 Data Accessibility and Visualization:

RS and GIS platforms provide easy access to a wide range of spatial data, enabling geotechnical engineers to visualize and analyze complex geospatial information effectively.

4.2 Cost and Time Efficiency:

By utilizing RS imagery and GIS tools, geotechnical investigations can be conducted remotely, reducing the need for extensive field surveys. This saves time and resources, especially for large-scale projects.

4.3 Multi-dimensional Analysis:

RS and GIS allow geotechnical engineers to analyze various data layers simultaneously, providing a comprehensive understanding of geological and geotechnical conditions. This multi-dimensional analysis aids in decision-making and risk assessment.

5. Limitations of Using RS & GIS in Geotechnical Applications

The use of Remote Sensing (RS) and Geographic Information Systems (GIS) in geotechnical applications has certain limitations that need to be considered:

Spatial and Temporal Resolution: RS data, especially satellite imagery, may have limitations in spatial resolution, meaning that it may not capture fine-scale details required for certain geotechnical analyses. Similarly, the temporal resolution of RS data may not be frequent enough to capture rapid changes in geotechnical conditions.

Data Availability and Accessibility: Acquiring high-quality RS data and GIS datasets can be costly, especially for specialized or high-resolution data. Additionally, certain regions may have limited data availability, particularly in remote or inaccessible areas, which can hinder the accuracy and comprehensiveness of geotechnical assessments.

Data Interpretation Challenges: Interpreting RS data and translating it into meaningful geotechnical information requires expertise and experience. Differentiating between natural and anthropogenic features, identifying geotechnical hazards, and accurately interpreting remote sensing indicators can be challenging without appropriate knowledge and ground truth verification.

Validation and Ground Truthing: RS and GIS data should be validated and calibrated using ground truth data, field surveys, or monitoring data. While RS data provides valuable insights, it is essential to validate and verify the results with ground-based measurements to ensure accuracy and reliability.

Limited Accessibility to Advanced RS Techniques: Some advanced RS techniques, such as Interferometric Synthetic Aperture Radar (InSAR) or hyperspectral imaging, may require specialized equipment, software, or expertise that may not be readily accessible to all geotechnical professionals or organizations.

Limited Coverage and Scale: RS data may have limitations in terms of coverage and scale. Some geotechnical applications require data at a very local or site-specific level, which may not be readily available or feasible to acquire through RS techniques.

Complexity of GIS Analysis: GIS analysis can be complex, requiring a certain level of technical knowledge and skills to effectively manipulate, analyze, and interpret geotechnical data. The learning curve associated with GIS software and the need for training and support can be a barrier for some users.

Uncertainty and Limitations in Data Interpretation: Geotechnical assessments based on RS and GIS data are subject to uncertainties and limitations. Factors such as atmospheric conditions, image processing techniques, and assumptions made during data analysis can introduce uncertainties and affect the accuracy of geotechnical interpretations.

Integration Challenges: Integrating RS and GIS data with other geotechnical datasets and models can be challenging due to differences in data formats, coordinate systems, and scales. Ensuring seamless integration and compatibility between various data sources and models requires careful data management and proper data integration techniques.

Continuous Monitoring Requirements: RS data may provide snapshots of geotechnical conditions at a particular time, but continuous monitoring of ground conditions is often necessary for accurate and dynamic geotechnical assessments. RS data alone may not capture the temporal variations and long-term behavior of geotechnical parameters.

While these limitations exist, RS and GIS still offer significant advantages in geotechnical applications. By understanding these limitations and using appropriate methodologies, validation techniques, and expertise, the potential benefits of RS and GIS can be maximized in geotechnical assessments and decision-making processes.

6. Compilation of GIS Software Options for Geotechnical Data Management.

There are several GIS software options available that can be used to manage geotechnical data effectively. Here are some popular GIS software packages commonly used for geotechnical data management:

ArcGIS: ArcGIS by Esri is one of the most widely used GIS software packages. It provides a comprehensive set of tools and functionalities for managing, analyzing, and visualizing geotechnical data. ArcGIS allows you to create geodatabases, store and manage geotechnical data in various formats, perform spatial analysis, and generate maps and reports.

QGIS: QGIS is a free and open-source GIS software that offers a user-friendly interface and a wide range of geospatial analysis capabilities. It supports various data formats, including geotechnical data, and provides tools for data editing, querying, analysis, and visualization. QGIS also has a strong plugin ecosystem that allows users to extend its functionality.

GeoStudio: GeoStudio is a specialized geotechnical modeling software suite that includes tools for geotechnical analysis, slope stability analysis, seepage analysis, and more. It integrates with GIS data, allowing you to import and export geotechnical data to and from GIS software for visualization and analysis.

Bentley gINT: Bentley gINT is a geotechnical software solution that includes a GIS module for managing and visualizing geotechnical data. It offers features for creating borehole logs, storing and managing subsurface data, and generating geotechnical reports. The GIS module in gINT allows you to integrate geotechnical data with spatial data for better visualization and analysis.

MapInfo Professional: MapInfo Professional is a GIS software package that provides tools for data management, mapping, and spatial analysis. It supports various data formats, including geotechnical data, and offers functionalities for querying, editing, and analyzing spatial data. MapInfo Professional also has capabilities for generating thematic maps and conducting spatial analysis for geotechnical purposes.

RockWorks: RockWorks is a specialized software package designed for geotechnical and geological data management and analysis. It offers tools for creating stratigraphic models, borehole data management, and geological mapping. While not a traditional GIS software, RockWorks integrates well with GIS platforms, allowing you to import and export data between the two for comprehensive analysis.

These software packages provide powerful tools for managing geotechnical data, performing spatial analysis, and generating maps and reports. The pros and cons of the at a glance software packages are listed in table-3 (Appendix). The choice of software will depend on your specific requirements, budget, and familiarity with the software. It's advisable to evaluate the features, capabilities, and compatibility with your data formats before selecting the most suitable GIS software for your geotechnical data management needs.

7. Discussion

The integration of Remote Sensing (RS) and Geographic Information Systems (GIS) has brought significant advancements to the field of Geotechnical Engineering. RS involves the collection of information about the Earth's surface using aerial or satellite-based sensors, while GIS enables the storage, manipulation, and interpretation of geospatial data. This abstract explores the diverse applications of RS and GIS in Geotechnical Engineering, highlighting their contributions to site selection and characterization, slope stability analysis, geohazard mapping and risk management, subsurface investigations, and infrastructure asset monitoring and management.

In the context of site selection and characterization, RS and GIS provide valuable tools for geotechnical engineers. RS data, such as high-resolution satellite imagery, helps identify potential geotechnical hazards, assess terrain conditions, and map geological features. By integrating various geospatial datasets into GIS platforms, engineers can make informed decisions regarding site suitability and optimize geotechnical investigations.

Slope stability analysis is another crucial area where RS and GIS play a significant role. RS techniques, including advanced image processing, enable the detection of ground movements, monitoring of slope deformations, and identification of landslide-prone areas. By integrating RS data with GIS-based slope stability models, engineers can perform comprehensive spatial analysis and assess the associated risks accurately.

Geohazard mapping and risk management benefit greatly from the integration of RS and GIS. By combining RS data with ground truth measurements, GIS platforms can generate accurate hazard maps that highlight areas prone to earthquakes, floods, or landslides. These maps serve as valuable tools for the development of effective mitigation strategies, land-use planning, and infrastructure design, ultimately minimizing potential risks and damages.

RS and GIS technologies also contribute significantly to subsurface investigations. RS data, such as airborne geophysical surveys and ground-penetrating radar, provide crucial information about subsurface conditions, including soil types, bedrock depth, and groundwater levels. Integration of this data with GIS aids in the design of foundations, tunnels, and underground structures, enhancing their safety and efficiency. Table-1 (appendix) gives brief outline of the research and application in various areas of geotechnical engineering.

Furthermore, RS and GIS are instrumental in the monitoring and management of infrastructure assets in geotechnical engineering. By utilizing RS data and GIS platforms, engineers can assess the condition of roads, bridges, and pipelines, detect deformations, and plan maintenance activities effectively. This proactive approach to infrastructure management ensures the longevity and reliability of geotechnical assets.

8. Conclusion

The integration of RS and GIS technologies in geotechnical engineering has significantly improved the accuracy, efficiency, and effectiveness of geotechnical investigations and analysis. These tools enable better-informed decision-making, site selection. The applications discussed in this paper demonstrate the substantial contributions of RS and GIS in site selection, slope stability analysis, geohazard mapping, subsurface investigations, and infrastructure monitoring and management. The continued development of RS and GIS technologies holds immense potential for further enhancing the capabilities and effectiveness of Geotechnical Engineering in the future.

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Appendix

Sr.No.		Researcher	Research Interest
1	Soil Survey, Reconnaissance Survey, Geotechnical Data management	Bui et al.(1995)	Soil survey- regional salinization risk mapping
		Satya Priya (1992)	Geotechnical data management and planning
		Rosen J.B. (2011)	Cut-off wall construction data management and decision making
		R. S. V. Player (2006)	Geotechnical data management using GIS
		Gandhimathi A. (2010)	Preliminary site investigation and soil characterization modelling
		Mary Labib et al. (2013)	GIS and geotechnical mapping of expansive soil
		AE AbdelRahman et al (2018)	Assessment of Soil Quality by Using Remote Sensing and GIS Techniques
		M.A. Elfadil et al (2018)	Soil profile modelling using geo- statistics and GIS
		Khatri, S. and S. Suman (2019)	Mapping of soil geotechnical properties using GIS
		Azougay, A. (2020)	The use of a GIS to study geotechnical problems in urban areas
		A. X. Zhu et al. (2001)	Soil mapping using GIS,
2	Ground water modelling	Fayer M.J. et al. (1995)	Estimation of recharge rate for ground water model
		Maitani et al. (2005)	Estimation of water seepage in tunnel and shortage of water reserve due to tunnel excavation
		Fares M. Howari et al. (2007)	Assessment and Development of Groundwater resources
		Kazakis, N. et al (2015), Khakhar, M. et al (2017)	Groundwater vulnerability and pollution risk assessment of porous aquifers
3	Geotechnical hazard Mapping, Erosion Landslide Monitoring and prediction, Slope Stability	Carrara, A.(1999)	Prediction and monitoring of landslide hazard
		Aleotti, P., & Chowdhury, R. (1999)	Landslide hazard assessment: summary review
		Guzzetti, F (1999)	Landslide hazard evaluation
		Meijerink et al. (1996)	Erosion modelling using flow accumulation
		Luna (1995), Kiremidjian (1997) and Miles & Ho(1995)	Evaluation of geotechnical hazard using GIS
		Esaki et al. (2000)	Hazard map of ground cave
		Sakellariou, M.G. (2001)	Estimation of slope stability
		Xie et al. (2003)	Estimation of 3-D slope stability
		Esaki et al. (2004)	Subsidence prediction due to underground mining
		Corominas, J (2005)	Landslide susceptibility analysis
		Pandey, A.C. (2007)	Landslide hazard zonation
		Jaiswal, P et al. (2011)	landslide hazard assessment
		Klose, C. D et al. (2012)	landslide susceptibility mapping

4	Soil Liquefection	Maitani et al. (2001)	Simulation of shear-flow coupling test
		Carr, L.P (2009)	Mapping Earthquake-Induced Landslides
		Megalooikonomou, V. et al. (2003)	Earthquake-induced soil liquefaction hazard mapping
		Ramakrishnan, D et al. (2006)	Mapping the liquefaction induced soil moisture changes using remote sensing technique
		Ishitsuka, K et al. (2011)	Detection and mapping of soil liquefaction
		Oommen, T et al. (2013)	Documenting earthquake-induced liquefaction using satellite remote sensing image transformations.
5	Rock Engineering	Roger and Drumm (1999), Geolith(2000) and Jurasius (2002)	Real time monitoring of incipient rock slope failure
		Esaki et al. (2006)	Rock Engineering
		Abellan, A. et al. (2009)	Rock fall hazard and risk assessment
		Singh, T. N. et al. (2016)	Rock mass characterization using remote sensing and GIS techniques:
		Mallick, J., & Baskey, S. K. (2017)	Rock slope stability analysis using remote sensing and GIS techniques

TABLE-1: Exclusive citations for RS & GIS applications in different geotechnical sectors.

City	Researchers	Year
Ahmedabad	Trivedi SS, Rao KS, Gupta KK (2007)	2007
	Trivedi SS (2011)	2011
	Rao KS, Thakker TP, Aggarwal A, Bhandari T, Kabra S (2012)	2012
Bangalore	Kumar, A., Anbazhagan, P., & Sitharam, T. G. (2013).	2013
Chandigarh	Mundepi AK (2008)	2008
Chennai	Suganthi A, Boominathan A (2006)	2006
	Boominathan A, Dodagoudar GR, Suganthi A, Uma Maheshwari R (2007)	2007
Dehradun	Mahajan AK, Slob S, Ranjan R, Spoory R, Champati Ray PK, van Westen CJ (2007)	2007
Delhi	Rao KS, Mohanty WK (2001)	2001
	Parvez IA, Panza GF, Gusev AA, Vaccari F (2002)	2002
	harma ML, Wason HR, Dimri R (2003)	2003
	Iyengar RN, Ghosh S (2004)	2004
	Mukhopadhyay S, Bormann P (2004)	2004
	Parvez IA, Vaccari F, Panza GF (2004)	2004
	Satyam DN (2006)	2006
	Mohanty WK, Walling MY, Nath SK, Pal I (2007)	2007
	Rao KS, Satyam DN (2007)	2007
Greater Hyderabad	Somayajulu, Y. K., & Raju, I. S. (2007)	2007
Hyderabad	Srinagesh, D., Sitharam, T. G., & Vipin, K. S. (2018)	2018
Haldia, Bengal	Mohanty WK, Walling MY (2008)	2008
India	Tandon AN (1956)	1956
	Krishna J (1959)	1959
	Guha SK (1962)	1962

	Gubin IE (1971), Gubin IE (1968)	1971
	Basu S, Nigam NC (1978)	1978
	Kaila KL, Rao M (1979)	1979
	Khattri KN, Rogers AM, Perkins DM, Algermissen ST (1984)	1984
	Bhatia SC, Ravi Kumar M, Gupta HK (1999)	1999
	Parvez IA, Vaccari F, Panza GF (2003)	2003
	Walling YM, Mohanty WK (2009)	2009
Jabalpur	Mishra PS (2004)	2004
Jammu city	Singh, Y., Mandal, P., & Shashidhar, D. (2010)	2010
Kolkata,	Mohanty WK, Walling MY (2008)	2008
	Vaccari F, Walling MY, Mohanty WK, Sengupta A, Panza GF (2011)	2011
	Sarkar, A., Sitharam, T. G., & Kumar, J. (2014)	2014
Mumbai	Raghukanth STG, Iyengar RN (2006)	2006
Mysore	Sitharam, T. G., & Kaynia, A. M. (2007)	2007
Review on all Indian Cities	Sitharam, T. G., & Anbazhagan, P. (2016)	2016
Sikkim	Pal I, Nath SK, Shukla K, Paul DK, Raj A, Thingbaijam KKS, Bandal BK (2008)	2008
Sikkim and Guwahati City	Nath SK, Thingbaijam KKS, Raj A (2008)	2008
Srinagar city, Kashmir valley	Mandal, P., Singh, Y., & Shashidhar, D. (2013)	2013
Surat	Thakker TP, Rathod GW, Rao KS, Gupta KK (2012)	2012

Table-2: Information on the researchers involved in seismic micro-zonation for Indian cities and pan-India.

Sr. No.	GIS Software	Pros	Cons
1	ArcGIS by Esri:	Comprehensive functionality for data management, analysis, and visualization.	Expensive, especially for commercial or enterprise-level licenses.
		Extensive support and resources available, including a large user community.	Steeper learning curve compared to some other GIS software.
		Wide range of extensions and add-ons to enhance functionality.	Some advanced features may require programming or scripting knowledge.
		Offers both desktop and web-based solutions.	
2	QGIS (Quantum GIS):	Open-source and free to use, making it accessible to a wide range of users.	Not as feature-rich as ArcGIS, particularly for advanced spatial analysis.
		Regular updates and improvements based on community contributions.	Limited technical support compared to commercial software.
		Extensible through plugins and libraries.	Plugin quality can vary, and some may lack documentation.
		User-friendly interface with intuitive tools and features.	
3	GRASS GIS:	Open-source and free GIS software with a strong focus on scientific research.	Steeper learning curve, especially for beginners.
		Advanced spatial analysis capabilities and modelling tools.	Less intuitive interface compared to some other GIS software.
		Integration with other open-source geospatial software.	Limited support for 3D visualization and cartographic design.
		Active development community and regular updates.	

4	MapInfo Pro:	User-friendly interface with easy-to-use mapping and analysis tools.	Relatively expensive, especially for commercial licenses.
		Strong data management capabilities, including extensive file format support.	Limited availability of advanced geo-processing tools.
		Good support for network analysis and location intelligence.	Smaller user community compared to some other GIS software.
		Offers both desktop and web-based solutions.	
5	Google Earth Pro:	Free version available with basic functionality.	Limited spatial analysis capabilities compared to full-fledged GIS software.
		Easy-to-use interface with intuitive navigation and visualization.	Less flexible data management options.
		Rich 3D imagery and satellite imagery coverage.	Online connectivity required for some features.
		Integration with other Google services.	
6	Global Mapper:	Affordable pricing compared to some other GIS software.	Interface can be overwhelming for beginners.
		Comprehensive data format support.	Less emphasis on cartographic design compared to other software.
		Extensive spatial analysis and processing tools.	Limited availability of advanced geo-processing algorithms.
		Good support for LiDAR data and 3D visualization.	
7	Geomedia	Fast querying and analysis	Confusing license tiers
		Strong cartography with smart labelling	Small user community for problem-solving
		Remote sensing with ERDAS Imagine	Cannot drag-and-drop files into GeoMedia
		All-purpose mapping with multiple layouts	Poor interoperability with other GIS formats
		Superior editing with smart snapping	
8	ILWIS	Monitoring and modelling the Earth system	Light on documentation and tutorial information
		Object-based image classification	Lacks advanced mapping features and layout support
		Land change modelling	Small community support and discussion forum
		2D and 3D visualization with time series	Sparse tools for advanced editing
		Free and Open Source Software	
		Image classification and remote sensing tools	
9	Bentley Map	CAD/GIS fusion	Limited GIS analysis tools
		3D viewing, analysis, and support	High cost for the license
		Fly-through, sunlight and shadow studies	Poor labelling and annotation
		Decent interoperability	

Table-3 Benefits and drawbacks of using different GIS software platforms.