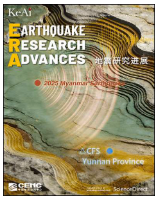
Earthquake Research Advances 6 (2026) 100399

Contents lists available at ScienceDirect

Earthquake Research Advances

journal homepage: www.keaipublishing.com/en/journals/earthquake-research-advances



The emerging roles of 3D and 4D geophysical and geological modelling in evaluating seismic risks: A critical review

Joseph Omeiza Alao

Department of Physics, Air Force Institute of Technology, Kaduna, Nigeria

ARTICLE INFO

Keywords:
Seismic hazard assessment
3D geophysical modelling
4D geophysical modelling
Hazard mitigation
Fault systems

ABSTRACT

Seismic hazard assessment (SHA) is crucial for mitigating earthquake hazards, particularly in tectonically active regions. This study critically examines the emerging roles of 3D and 4D geophysical and geological modelling in assessing SHA, focusing on advancements, applications, and limitations. 3D geophysical modelling provides high-resolution spatial representations of fault networks, stress distributions, and seismic-prone zones. In contrast, 4D geophysical modelling integrates temporal dynamics to analyze subsurface variations or fault systems over time. Based on previous studies, the quantitative data highlight the effectiveness of real-time seismic monitoring, with stress accumulation rates ranging from 0.01% to 50% during seismic events. Time-lapse seismic data improves forecasting precision, with early warning detection reducing seismic uncertainties by over 30%. Additionally, studies show that enhanced fluid migration tracking using 4D seismic modelling, leading to a 25% increase in hydrocarbon recovery efficiency. These advancements aim in urban planning, infrastructure resilience, and hazard mitigation strategies. However, challenges remain in data acquisition, computational demands, and model interpretation. The integration of artificial intelligence and high-performance computing is expected to improve predictive modelling accuracy, ensuring more effective SHA. The findings emphasize the importance of geophysical modelling in disaster preparedness, reinforcing the need for technological advancements to enhance seismic hazard mitigation strategies and infrastructure safety.

1. Introduction

Seismic hazards remain a threat to infrastructure, economic stability, and human well-being worldwide, especially in seismically active regions. In tectonically active areas, where the interaction of geological forces might result in catastrophic earthquakes (Fan et al., 2019), these dangers are especially noticeable. More than ever, there is a need for sophisticated technologies to anticipate and reduce seismic dangers due to growing urbanization and population density (Ciucci et al., 2022; Bal and Smyrou, 2022; Chen, 2025). Applications of geophysical modelling have become a fundamental component of SHA (Jena et al., 2020; Kato, 2022), providing an unmatched understanding of the processes of the Earth's subsurface. By bridging the gap between theoretical geoscience and real-world applications (Omeiza et al., 2023; Alao et al., 2023), geophysical modelling provides adequate understanding and visualize the intricate mechanisms governing seismic activity (Rebetsky & Stefanov, 2023). Geophysical modeling has been referred to as the formation of a computational or mathematical framework of the Earth's physical properties and processes, which combines data from different fields such as gravity, seismology, magnetism, and electromagnetism to model subsurface structures and dynamics (Pears and Chalke, 2016). It enhances the interpretations of the Earth's processes, including earthquake behaviour, tectonic plate movement, and resource distribution. Study indicates that geophysical modelling is crucial in the prediction or reconstruction of future and past geophysical settings and environmental planning, reduction of disaster risk, as well as natural resource exploration (Bal and Smyrou, 2022; Hasan and Shang, 2022).

E-mail address: alaojosephomeiza@gmail.com.

Peer review under the responsibility of Editorial Board of Earthquake Research Advances.

Production and Hosting by Elsevier on behalf of KeAi

https://doi.org/10.1016/j.eqrea.2025.100399
Received 3 May 2025; Received in revised form 14 June 2025; Accepted 30 June 2025

The capacity of geophysical modelling to locate fault lines, evaluate stress distributions, and forecast probable earthquake situations makes it significant (Hasan and Shang, 2022). Though geophysical models may not always possess all the answers to subsurface targets due to imperfections in subsurface geology (Alao et al., 2024). However, the application of 4D geophysical modelling that considers time as an active dimension has greatly improved the ability to investigate seismic processes not only in space, but also temporally. Whereas 3D modelling provides high-fidelity snapshots of stationary subsurface geometries, 4D modelling offers a temporal perspective on stress evolution, strain accumulation, and fault deformation. While heretofore used at the reservoir or basin level to track fluid migration and mechanical deformation, recent progress has seen its use extended through tectonic environments (Davies et al., 2004). From such environments, 4D modelling makes possible the study of how stresses accumulate and release along traces of active faulting, providing insightful information on the nucleation and recurrence of earthquakes, thus enabling additional nuanced seismic hazard considerations. SHA development has moved on from the single use of empirical data to the application of complex computational modelling methodologies (Gigliotti and Oliveira, 2020). In the process, 3D and 4D geophysical and geological modeling have been at the forefront—not just fault system mapping and seismic risk evaluation but also optimizing reservoir characterization and seismic interpretation (Burlington-House, 2019). These modelling methods yield high-resolution information on subsurface geometry and temporal evolution, which are critical for maximizing resource discovery, achieving maximum hydrocarbon recovery, and preventing induced seismicity during reservoir production.

Beyond conventional applications, the growing functions of 3D and 4D geophysical modelling address the changing problems brought by seismic hazards in a changing global environment (Nanda, 2021). Forecasting earthquake probabilities, evaluating the resilience of vital infrastructure (Rezaei and Naderpour, 2020), and guiding urban planning and disaster preparedness plans have all benefited greatly from these models. Moreover, developments in computational methodologies and data collection have substantially boosted the accuracy and scalability of these models (Xu et al., 2021; Martinez et al., 2021), making them vital tools for academics and policymakers alike. This review aims to critically examine the emerging roles of 3D and 4D geophysical modelling in evaluating seismic hazards, focusing on their advancements, applications, and limitations. By combining recent research and case studies, this review aims to provide a thorough knowledge of how these models contribute to seismic hazard mitigation. It also delves into issues of data quality, computational demands, and model interpretation, providing insights for future studies and development. Finally, this study emphasizes the importance of embracing cutting-edge geophysical modelling tools to improve our ability to anticipate, plan for, and respond to seismic events, ensuring a safer, more resilient future for populations worldwide.

2. Fundamentals of 3D and 4D geophysical modelling

The elastic wave travels through Earth materials is governed by their mechanical properties, which involve P waves and S waves described by the wave Eq. (1) (Telford et al., 1990),

$$\nabla^2 u - \frac{1}{v^2}\frac{\partial^2 u}{\partial t^2} = 0 \tag{1}$$

where t represents time, v represents wave velocity, and u represents displacement. In 3D modeling, the equation is solved in three dimensions space to build subsurface structures such as faults, lithological contacts, and stress fields. 4D modeling goes one step further by incorporating time so that dynamic monitoring of such alterations as fluid migration, stress redistribution, and fault activation can be carried out. These models are based on seismic reflection and refraction data, where the acoustic impedance variation.

$$z = \rho v \tag{2}$$

Eq. (2) exhibits changes in rock properties. The collection of seismic data, which could be through microseismic, refraction, or reflection techniques, detects how elastic waves travel via various geological strata (Alao et al., 2025). The responses of these waves to different rock layers and properties, such as elasticity and density, unveil stratigraphic and structural information. 3D geophysical models have emerged as a key tool for identifying and predict fractures, fault lines, assess stress distributions, and potential earthquake-prone areas. 4D time-lapse seismic surveys compare follow-up datasets to identify subtle temporal variations and enhance risk prediction and reservoir surveillance. Niri (2018) reports that integrating 3D and 4D seismic data greatly enhances seismic risk estimation and reservoir description. Likewise, Applied Seismic Methods underscores that wave propagation by seismic waves gives rise to imaging the interior of Earth under both static and dynamic conditions. Geophysical modelling has transformed the study of SHA, providing methods for visualizing and analyzing the Earth's subsurface with remarkable precision, thereby improving seismic risk assessments (SRA). Geophysical modelling is fundamentally about integrating geological, geophysical, and geotechnical data to produce models of subsurface structures. These models are vital for understanding seismic hazards because they allow researchers to detect fault lines, evaluate stress distributions (Zhan et al., 2022; Bapir et al., 2023; Yang et al., 2024), and predict future earthquake scenarios.

2.1. *3D geophysical/geological modelling*

The 3D geophysical modelling is a major improvement over older 2D methods. While 2D modelling provides cross-sectional views of subsurface structures (Fig. 1), 3D modelling generates comprehensive spatial representations that capture the complexity of geological formations in three dimensions (Zhang et al., 2022). This tool offers a more detailed examination of SHA by visualizing fault networks, stratigraphic layers, and stress fields. 3D modelling in seismic investigations is used for hazard assessment, infrastructure development, and resource discovery. 3D geophysical and geological modelling has transformed seismic risk estimation by offering comprehensive spatial representations of underlying structures (Wang et al., 2025), which reflect potential SHA. These models integrate seismic data, geological surveys, and geophysical measurements to create high-resolution pictures of fault lines, stress zones, and possible earthquake-prone locations (Wu et al., 2019). One of the emerging responsibilities of 3D modelling is its capacity to enhance hazard assessment and mitigation tactics (Royer et al., 2015). By studying underlying formations with precision, researchers can locate active fault systems and estimate stress accumulation, enhancing earthquake forecasting. Furthermore, 3D models are increasingly incorporating machine learning algorithms to improve data interpretation and optimize seismic forecasts. By providing a richer image of subsurface dynamics, 3D modelling improves the accuracy of seismic risk estimations and informs decision-making processes. Another vital utilization of 3D is in urban planning and infrastructure resilience (Nanda, 2021). Governments and engineers use 3D seismic models to assess ground stability before constructing buildings, bridges, and other critical infrastructure. This proactive technique reduces the risks connected with seismic activity and ensures structural integrity in earthquake-prone zones (Bellounis et al., 2025).

In application, 3D geophysical and geological modeling plays an essential role in seismic hazard assessment through high-resolution imaging of lithologic variations, fault zones, and subsurface geometry (Fig. 2). These models, as seen in Fig. 2a and 2b: improve site-specific evaluation, particularly in urban or karst terrains, by including geophysical information to assess ground stability and potential seismic amplification. This enhances risk-informed planning for disaster

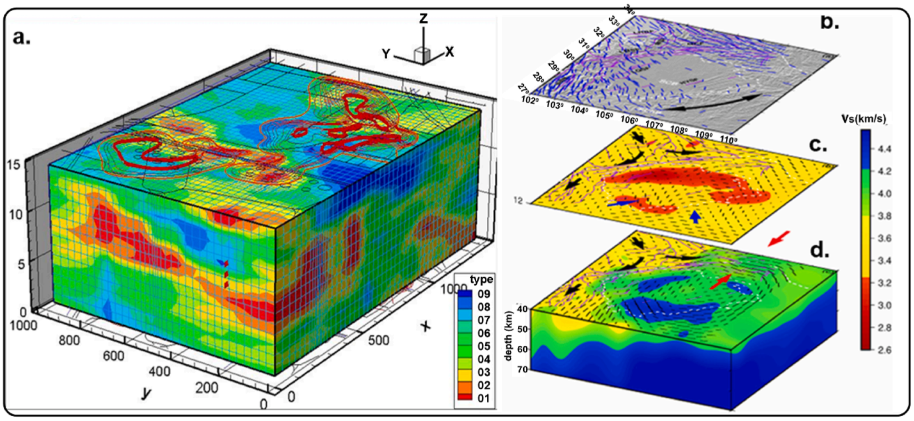


Fig. 1. Shows a perspective view of the 3-D shear-wave velocity and azimuthal anisotropy model for the Sichuan Basin and surrounding regions. The faults and block borders are indicated by purple and white lines (see Fig. 1 for details). The rapid axes identified by teleseismic shear wave splitting analysis are shown in (a) 3D Geological model (the legend “Type” represents a classification metric derived from clustering analysis of subsurface properties as shown in Fig. 2. The red contours in Panel (a) denote regions of enhanced seismic activity or anomalies identified through inversion modelling). In (b), blue short lines indicate the fast axes determined by teleseismic shear wave splitting analysis (Chang, et al., 2008, 2017). Double-headed black arrows show the possible rotation in the southeast of the Sichuan Basin (Wang et al., 2014; Tong Y, 2019). In (c) and (d), short black lines represent the azimuthal anisotropy, and the background color shows shear wave velocity. Black arrows represent the possible movement direction of the crustal materials, blue and red arrows show the possible compressive stress distribution derived from the anisotropy pattern and tectonic history.

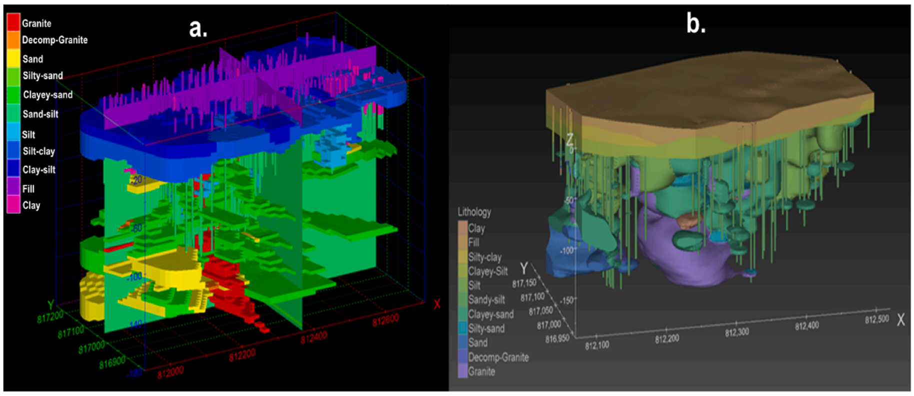


Fig. 2. 3D geophysical model (a) is a 3D geophysical model created for the HongKong Geological Survey, which was investigating Karst geology at the site of a multi-tower high-rise development. (b) is another 3D geophysical model, which was used to create complex models that accurately represent subsurface lithology as seen in the 3D Interactive Model in Fig. a (Ctech, 2024).

mitigation and infrastructure. As Cao et al. (2024) explicate, 3D modelling enhances the accuracy of hazard prediction by implementing multisource data and producing dynamic geological interpretations. Despite its advantages, 3D modelling presents problems, including data collecting complications, computing loads, and interpretation issues. High-quality seismic data is crucial for accurate modelling, but getting such data can be costly and technically challenging. Additionally, processing large volumes of geophysical data requires high-performance computing resources, making it unattainable for some research institutions. To sum up, 3D geophysical and geological modelling is essential for assessing seismic risk since it provides better hazard assessment and increased predictive power (Fu et al., 2024). As technology progresses, combining artificial intelligence and real-time monitoring will further enhance these models, making seismic risk evaluation more precise and effective.

2.2. 4D geophysical/geological modelling

4D geophysical modeling is an advanced method that extends conventional 3D subsurface tomography by adding time as a fourth dimension. Steffen, Robertson, and Kirsten (SRK) Consulting accounts for developing 4D geological mapping through regional geophysics, utilizing time-based modelling for structural evolution and tectonic stress regimes (Williams and Gleeson, 2007). SRK's innovation lies in incorporating time factors into structural interpretation, specifically within the more challenging geological terranes such as Archaean cratons, for SHA. The Dredging Association offers a case study of 4D resistivity modeling for subsurface geology site exploration. Although engineering and environmental applications are emphasized, the method demonstrates the use of time-lapse geophysical data to locate subsurface changes, principles that are increasingly incorporated into tectonic-scale studies. SRK Consulting provides a summary of how 4D models enable the monitoring of dynamic subsurface processes, which is key to understanding stress accumulation and release. The capabilities of georeferenced 4D models used in on-site investigations for dredging operations are demonstrated by two recent case studies from the USA. An innovative geophysical technique called Aquares resistivity serves as the foundation for all 4D models. Previous articles explain the fundamentals of this approach (Brabers et al., 2017). The initial is a dredging project at Port Canaveral, Florida's access canal. In the second case, muck deposits are being mapped as part of a site evaluation for a restoration project at Rockledge in the Indian River Lagoon, Florida.

4D geophysical modelling, which builds on the foundation of 3D modelling (Fig. 3), incorporates the dimension of time, enabling the

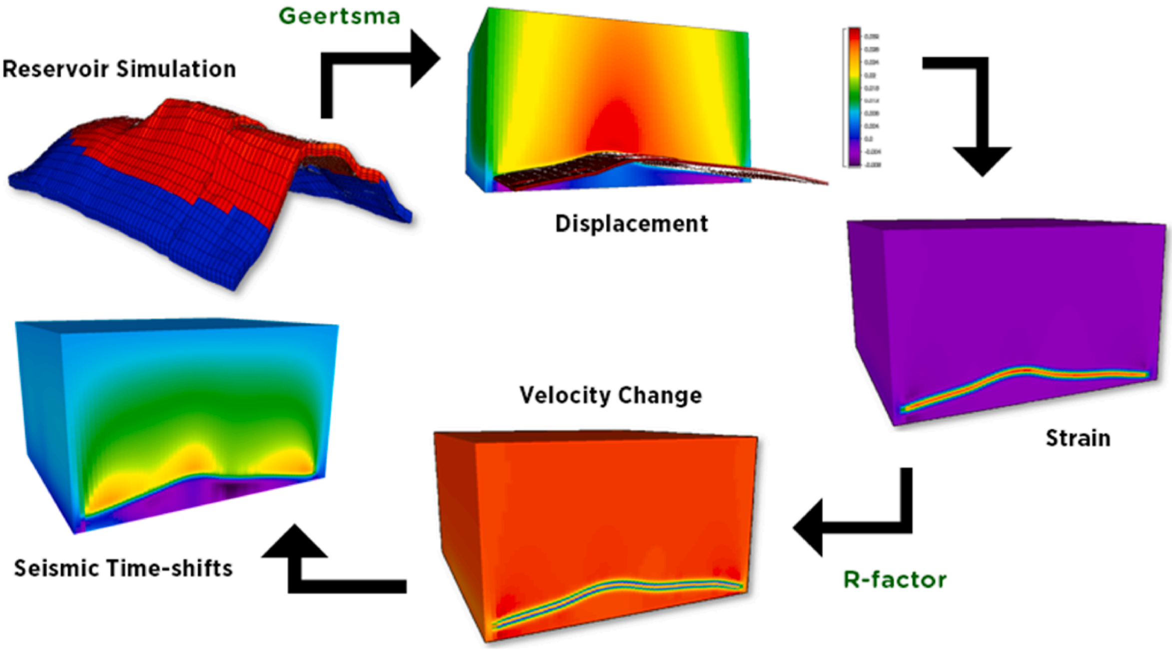


Fig. 3. Geomechanical modeling workflow for reservoir deformation analysis, which is an extension of the 3D geomechanical model to the 4D geomechanical model (Toosi, 2022). The model is 2.5 km × 2.5 km horizontally projected and 3.0 km in depth in the *z*-direction. The five panels show the successive simulation steps. (a) Reservoir Simulation: simulates the pressure evolution of the reservoir domain. (b) Displacement plots surface and subsurface displacements due to fluid withdrawal based on the Geertsma factor. (c) Strain plots deformation intensity, i.e., in dilation or compaction zones. (d) Velocity Change shows modifications of seismic velocities due to stress redistribution. (e) Seismic Time-Shift plots the temporal delay of wave passage, estimated from R-factor and strain inputs.

dynamic analysis of subsurface processes. The 3D renderings with colour gradations present spatial and temporal variations, offering insights into coupled geomechanical-seismic responses pertinent to reservoir management and risk reduction. The temporal aspect is crucial for understanding the progression of stress accumulation and release, which are key indicators of seismic activity. By monitoring changes in subsurface structures over time, researchers can provide insights into the evolution of fault systems and the potential for future (Burlington-House, 2019). Real-time monitoring, earthquake forecasting, and long-term seismic risk assessment are all examples of 4D modelling applications in seismic studies (Sawyer, 2025). By capturing the dynamic nature of geological processes, 4D modelling provides a more holistic approach to seismic risk appraisal. With its ability to provide dynamic insights into subsurface changes over time, 4D geophysical and geological modelling has become a potent tool for assessing seismic risk. Researchers can monitor geological and geophysical changes driven by stress accumulation, fluid migration, and fault movements through 4D modelling, which adds a temporal dimension, in contrast to 3D modelling, which provides static representations.

One of the main functions of 4D seismic modelling is its use in real-time monitoring of seismic activity (Niri, 2018). By analyzing time-lapse seismic data, scientists can detect subtle changes in subsurface structures, improving earthquake forecasting and hazard assessment. This capability is especially valuable in regions with active fault systems, where continuous monitoring can enhance early warning mechanisms. While 3D modelling provides static representations, 4D modelling incorporates the temporal dimension, enabling researchers to track geological and geophysical variations driven by stress accumulation, fluid migration, and fault movements. Additionally, 4D modelling aids reservoir characterization, enabling geoscientists to understand fluid dynamics within subterranean formations (Rebetsky & Stefanov, 2023). This is critical for analyzing pressure variations and stress redistribution, which can influence seismic activity. Research has shown that using machine learning algorithms with 4D seismic data improves prediction accuracy (Bauer et al., 2010), allowing for more successful risk reduction techniques. Notwithstanding its benefits, 4D modelling has drawbacks, such as high processing requirements (Skyttä et al., 2011), complicated data collection, and difficulty with interpretation. Time-lapse seismic data processing is resource-intensive and necessitates sophisticated computing infrastructure. Furthermore, maintaining data resolution and consistency over various periods are still a technical challenge (Wang et al., 2024). To sum up, 4D geophysical and geological modelling is essential for seismic risk assessment because it provides dynamic insights that enhance hazard assessment and disaster preparedness. As technology develops, incorporating artificial intelligence and cloud computing will further enhance these models, increasing the accuracy and efficacy of seismic risk assessment.

2.3. *Differences and complementary roles*

Although the objectives of 3D and 4D geophysical modelling are similar, their approaches and applications differ significantly. Spatial analysis is the main emphasis of 3D modelling, which produces intricate depictions of underlying structures at a particular moment in time. 4D modelling, on the other hand, emphasizes temporal dynamics and records how underlying structures evolve over time. Because they focus on various facets of seismic risk assessment, these distinctions make the two methodologies complementary. For instance, 4D modelling is better for tracking dynamic processes and forecasting future seismic events, whereas 3D modelling is best for locating fault networks and evaluating static hazards. When combined, these models provide a comprehensive framework for understanding and mitigating seismic hazards.

3. Applications in seismic risk evaluation

The incorporation of 3D and 4D geophysical modelling has revolutionized seismic risk assessment by providing previously unheard-of insights into underlying processes. By improving the accuracy of seismic hazard assessments, these cutting-edge modelling tools allow for more efficient catastrophe preparedness and mitigation plans. Researchers can identify fault lines, stress distributions, and possible seismic hotspots by using 3D seismic modelling, which offers a comprehensive spatial depiction of geological formations (Nanda, 2016). This technology ensures that infrastructure is earthquake-resistant, which is crucial for urban planning (Pessina and Meroni, 2009). Furthermore, the monitoring of subsurface changes over time is made possible by 4D seismic modelling, which integrates time-lapse data. When evaluating fluid migration, reservoir depletion, and stress accumulation, which are crucial elements in seismic risk assessment. The oil and gas sector is one of the most important users of 3D and 4D seismic modelling, as it facilitates reservoir management and improves hydrocarbon recovery (Niri, 2018). Geophysicists can forecast seismic activity associated with extraction operations by regularly updating seismic data, which reduces the risk of induced earthquakes (Odoh et al., 2024). These models also support early warning systems that provide real-time data for risk assessment and earthquake forecasting. By combining seismic modelling with machine learning and artificial intelligence, risk assessment is further improved, allowing for predictive analytics that improve decision-making. The implementation of 3D and 4D geophysical modelling is a critical step in protecting infrastructure and communities as seismic hazards continue to present difficulties on a worldwide scale.

Integrating 3D and 4D geophysical modelling has greatly improved the accuracy of seismic hazard assessment, which is an essential part of earthquake risk mitigation. Researchers can more accurately forecast and prepare for seismic events thanks to these sophisticated models, which provide comprehensive insights into fault lines, stress distributions, and potential seismic zones. Geophysicists can precisely map fault systems thanks to the high-resolution spatial representation of subsurface structures provided by 3D seismic modelling (Nanda, 2016). Researchers can find regions of stored stress that could cause earthquakes by examining the propagation of seismic waves. To guarantee resilience against seismic disasters, this technique is extensively utilized in infrastructure building and urban planning (Jena et al., 2020). The use of time-lapse data in 4D seismic modelling adds a dynamic component to hazard assessment. Geophysicists can watch fluid movement and stress evolution, two important markers of seismic activity (Bacon et al., 2015), by continuously observing subsurface changes. This strategy is especially useful in areas where industrial operations, such as oil and gas extraction are likely to cause induced seismicity. Furthermore, real-time risk assessment is made possible by the enhancement of prediction capacities through the integration of seismic modelling with machine learning algorithms. These models provide vital information for catastrophe preparedness and response plans, supporting early warning systems. Fig. 4 is a local-scale seismic risk assessment framework and toolset showing the local-scale hazard estimation over global-scale modelling at a site-specific seismic risk assessment. The framework is composed of four important elements: Hazard, Vulnerability, Exposure, and Loss, and collectively, an integrated seismic risk assessment system. The Hazard tool provides an estimate of the likelihood and magnitude of future earthquakes at the site based on seismic sources, recurrence rates, ground motion prediction equations and site effects. It is presented graphically as a seismic waveform and probabilistic shaking intensity map, which are used as inputs to subsequent-stage vulnerability and loss modeling. The integration of all these factors enables more accurate risk estimation and informs decision-making for disaster mitigation and preparedness. This process supported by the European Commission's Joint Research Centre, National Risk Assessment Partnership (Poljansek et al., 2021), and Garcia-Fernandez et al. (2023) in their investigation of multi-scale seismic risk models (Garcia et al., 2023). Therefore, an important development in earthquake risk assessment is the use of 3D and 4D geophysical modelling in seismic hazard assessment, which creates more effective mitigation methods by leveraging these technologies, thereby protecting infrastructure and communities.

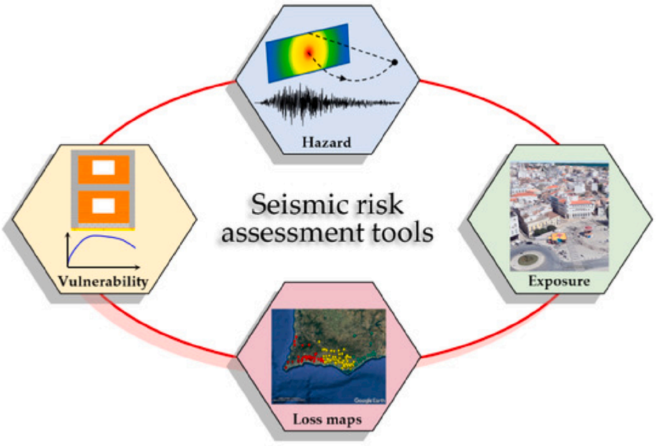


Fig. 4. Local-scale seismic risk assessment framework and toolset that illustrates a site-specific SHA, emphasizing localized hazard evaluation rather than global-scale modeling (Estêvão, 2018).

In geophysics, it has long been difficult to make more accurate earthquake predictions. However, by offering an in-depth understanding of fault dynamics and stress accumulation, the development of 3D and 4D geophysical modelling has greatly enhanced forecasting capabilities. Using 3D seismic modelling, geophysicists can precisely visualize fault structures and pinpoint stress concentrations that could trigger seismic activity (KAUST, 2025). Researchers can determine the probability of future earthquakes by examining subsurface deformation and seismic wave propagation (Bertinelli et al., 2023). This approach has been important in refining danger maps and developing risk-reduction measures. Time-lapse data is incorporated into 4D seismic modelling, which improves earthquake prediction by monitoring fault system changes over time (Liu et al., 2019). Scientists can spot early warning signs of seismic activity by closely observing the history of stress and fluid migration. This dynamic technique is especially useful in areas where industrial activity is likely to induce seismicity (Klin et al., 2025). Earthquake forecasting has been considerably improved by recent developments in physics-based simulations. Predictive models have been improved by studies that use 3D finite element dynamic earthquake simulators to show how complicated fault geometry affects rupture patterns (Bertinelli et al., 2023). High-resolution 3D models have also shed light on unanticipated ground shaking and supershear rupture rates (Liu et al., 2019).

The evaluation of critical infrastructure susceptibility to seismic occurrences has been transformed by the use of 3D and 4D geophysical modelling. Engineers and legislators may put preventative safety measures into place thanks to these sophisticated models, which provide comprehensive insights into structural flaws (Zhang et al., 2018). By providing high-resolution spatial representations of subsurface structures, 3D seismic modelling enables professionals to spot stress distributions and fault lines that can jeopardize the stability of infrastructure (Kim et al., 2024). This method is commonly utilized in urban planning to make sure that transportation networks, buildings, and bridges are made to withstand seismic forces. By monitoring alterations in geological formations over time, 4D seismic modelling that incorporates time-lapse data improves infrastructure safety (Kim et al., 2024). This dynamic technique is especially useful for evaluating material degradation, anticipating probable failure locations, and monitoring aging buildings. Engineers can improve reinforcing plans and risk assessments by incorporating past seismic data. Additionally, seismic modelling and machine learning techniques enhance predictive capabilities, allowing for real-time risk assessment. Early warning systems are supported by these models, which offer vital information for catastrophe reaction and preparation (Swallow and Zulu, 2019). By guaranteeing resistance against future earthquakes, the use of 3D and 4D geophysical modelling in infrastructure safety constitutes a substantial improvement in seismic risk mitigation.

4. Case studies demonstrating impact

Improvements in hazard assessment and forecast accuracy are demonstrated by case studies on 3D and 4D geophysical and geological modelling in seismic risk assessment. To simulate seismic activity and support risk-reduction techniques, these models incorporate spatial and temporal data. For example, research has shown that 4D modelling improves early warning systems by facilitating real-time fault movement monitoring (Davies et al., 2004). Subterranean structures have been mapped using 3D seismic tomography to pinpoint possible earthquake-prone areas (Perkins, 2019; Brett et al., 2022), providing insights into ground deformation and seismic wave propagation. Machine learning has further enhanced prediction capacities through the refinement of these models. In earthquake-prone areas, these approaches are increasingly used to improve response and readiness plans. For instance, a study examines the role of Time Lapse (4D) seismic technology as a reservoir monitoring and surveillance tool, which highlights the numerical advancements in 4D seismic technology, emphasizing its role in reservoir surveillance and hydrocarbon recovery (Sambo et al., 2020). Over the past decades, improvements in seismic acquisition and processing have strengthened its application, particularly in monitoring CO_2 storage sites and unconventional reservoirs. The study underscores the importance of integrating seismic attributes rather than using them in isolation to improve dynamic reservoir monitoring. However, rock physics modelling uncertainties and pore-scale variations remain challenges. Future research should focus on integrating 4D seismic with geomechanics and fluid flow to improve accuracy. The article highlights the numerical significance of 4D seismic technology in reservoir management, emphasizing its ability to track changes in fluid saturation and reservoir pressure over time. The time lag between surveys, ranging from 4 to 6 months for enhanced oil recovery (EOR) to 2–5 years for mapping undrained hydrocarbons, plays a crucial role in optimizing field development (Mitra, 2022). The study underscores the economic benefits demonstrated since the 1990s, particularly in complex reservoirs. However, integration challenges with other geophysical techniques remain a key area for future research.

Another study emphasizes the numerical significance of 3D Geoseismic interpretation in hydrocarbon exploration, particularly in the Cooper Basin region of Australia (Bashir et al., 2025). The research highlights the identification of trap structures using seismic attributes such as dim, flat, and bright spots, which are crucial for reservoir characterization. The integration of amplitude, frequency, and phase data enhances target illumination, improving signal-to-noise ratios and fault detection. However, complex stratigraphic layers introduce uncertainties, necessitating further advancements in geophysical methodologies for optimal resource evaluation. A similar study emphasizes the numerical integration of 3D and 4D seismic impedance data into reservoir simulation workflows, there by reducing uncertainties in hydrocarbon distribution (Maleki et al., 2018). The Norne benchmark field, a faulted sandstone reservoir, serves as a case study that demonstrates improved understanding of reservoir behaviour. The circular workflow enhances production forecasting by aligning static and dynamic models with observed seismic and well production history data. However, uncertainties in petro-elastic modelling remain a challenge, necessitating further deterministic and probabilistic history matching studies for optimal reservoir management. A study also shows actual correlations between production in unconventional shale in the Horn River Basin and microseismic, 3D inversion characteristics, and 4D seismic data (Iverson et al., 2013). The aforementioned instruments, along with a thorough examination of stimulated rock volume, are used to explain production variances. It has been demonstrated that a fault that crosses the north part of a well pad causes these production differences to arise from a highly stressed zone. The 4D reaction and the locations of microseismic events determine estimates of stimulated rock volume. It has been demonstrated that brittle rock experiences high *b*-values in a lower stress regime, while ductile rock experiences low *b*-value phases in a comparatively greater stress regime. The numerical significance of 3D and 4D seismic data in reservoir characterization was examined using high-resolution 3D seismic imaging, enabled by regular, close-grid spatial sampling, which enhances rock-fluid property estimation, improving reserve calculations and production planning. The migration of prestack data in the depth domain (PSDM) improves seismic accuracy but has limitations (Nanda, 2021). 4D seismic, with time-lapse monitoring, aids in reservoir geomechanics, tracking fluid flow changes and enhanced oil recovery (EOR) efficiency. However, workflow integration challenges persist, requiring further seismic reservoir monitoring (SRM) advancements for optimal hydrocarbon recovery (Pratama and Latiff, 2021).

A study employs advanced 3D geological modelling to reconstruct the subsoil structure of Nafplio, integrating engineering and geophysical data for seismic risk assessment. The model highlights spatial relationships between geological units, crucial for understanding local seismic amplification (Fiorucci et al., 2024). A 4D approach assesses the temporal evolution of coastal deposits, revealing geomorphological changes and erosion dynamics. Numerical simulations of seismic wave propagation identify amplification effects, particularly in soft soils and ridge areas. The findings enhance seismic microzonation, aiding urban planning and heritage preservation. By integrating geological modelling and numerical analysis, the study provides a robust framework for disaster mitigation strategies in earthquake-prone regions, emphasizing the importance of geological complexity in seismic response evaluations. Another study presents an integrated 3D geological modelling and geophysical inversion approach applied to the Boulia region, Queensland, using gravity and reflection seismic datasets to refine subsurface boundaries (Rashidifard et al., 2024). A cooperative geophysical inversion enhances accuracy by incorporating petrophysical constraints and seismic impedance data. The 3D modelling reveals major rock unit geometries, while a 4D analysis captures temporal variations in subsurface structures. Numerical simulations confirm density contrasts influencing geological interpretations. The findings aid mineral exploration by improving subsurface imaging and informing drilling decisions. The study underscores the value of integrating geological modelling with geophysical inversion to refine structural insights and optimize resource assessments in complex geological settings.

A 4D seismic exploration was examined in Russia, analyzing sequential 3D surveys conducted over time to monitor reservoir development, highlighting numerical data on seismic amplitude shifts and velocity changes due to fluid displacement and pressure variations (Geomodel, 2024). The study underscores the challenges of data consistency across multiple surveys and the need for advanced inversion techniques. Findings suggest 4D seismic can optimize production strategies, particularly offshore, where stable acquisition methods improve data reliability. Despite limited onshore applications, the study advocates broader adoption of 4D seismic for enhanced reservoir management. The implications emphasize technological advancements in seismic modelling to refine hydrocarbon recovery efficiency (Pratama and Latiff, 2021). A study explores innovative processing adaptations for deepwater seismic data, advancing 3D and 4D imaging techniques for complex reservoirs (Ogu et al., 2023). The 3D imaging integrates multi-frequency and multi-azimuthal data, improving subsurface resolution and fault-zone detection. The 4D imaging utilizes time-lapse monitoring to track reservoir changes, aiding fluid movement analysis and production optimization. Numerical simulations demonstrate enhanced seismic inversion, refining reservoir models and guiding extraction strategies. Machine learning aids in event detection and noise suppression, streamlining data interpretation. These innovations improve seismic survey efficiency, reducing costs while maximizing data accuracy. The study underscores the significance of integrating real-time analytics with seismic imaging for informed deepwater exploration and reservoir management.

A noteworthy study presents a 3D discontinuous Galerkin method for simulating nonlinear seismic wave propagation, validated against analytical solutions and applied to the 2015 M_W 7.8 Gorkha earthquake (Niu et al., 2025). The 3D model captures coseismic wave-speed reductions ranging from $<0.01\%$ to $>50\%$, with amplification in soft sediments. A 4D framework assesses spatial-temporal variations, correlating changes in wave speed with fault slip and basin depth. Numerical simulations highlight nonlinear site effects that influencing ground motion and seismic hazard assessment. Findings demonstrate the importance of integrating experimentally constrained nonlinear models into seismic analysis, improving predictions of earthquake impacts and guiding infrastructure design for better resilience against strong ground shaking. Another discusses preprocessing quality control (QC) for land 3D seismic data, focusing on survey design, noise properties, first breaks, and normal moveout to enhance data integrity (Raef, 2009). The 3D numerical analysis ensures accurate geometry assignments, minimizing errors in spatial positioning and vertical stacking. A 4D approach aids time-lapse seismic monitoring, particularly at CO_2 injection sites, assessing subtle reservoir seismic anomalies (Raef, 2009). The numerical findings reveal critical inconsistencies in preprocessing that could impact seismic interpretations. By refining QC techniques, the study highlights improved seismic imaging for enhanced reservoir characterization, thereby supporting effective monitoring strategies in geological sequestration and hydrocarbon exploration (Raef, 2009). These insights contribute to reliable seismic processing workflows and cost-effective data acquisition.

A 4D geomechanical flow model integrating 3D seismic inversion data was employed to assess the reservoir. The 3D model builds geological facies using seismic interpretations, guiding fluid flow simulations (Herwanger et al., 2016). The 4D component incorporates temporal variations, predicting stress evolution due to production and injection. Numerical analyses evaluate wellbore stability, injection pressure limits, fault reactivation risks, and time-lapse seismic effects. Findings highlight the significance of coupled geomechanical modelling for optimizing field operations, mitigating drilling hazards, and refining hydraulic stimulation strategies. The study underscores the value of integrating seismic, petrophysical, and geomechanical data to improve reservoir management and enhance predictive capabilities for operational decision-making in complex subsurface environments. Combined 3D and 4D seismic data in reservoir modelling were examined, emphasizing their roles in static and dynamic characterization (Niri, 2018). The 3D seismic data enhance structural interpretations, aiding in defining reservoir geometries and property distributions (Zhan et al., 2022). Meanwhile, 4D seismic data track production-induced changes, capturing fluid movement and pressure variations over time (Niri, 2018). Numerical analyses demonstrate that seismic inversion techniques thereby refine porosity and permeability estimates, improving hydrocarbon recovery strategies (Niri, 2018). The study underscores the importance of time-lapse seismic monitoring in reducing reservoir uncertainties and optimizing field development. By integrating seismic attributes with petrophysical modelling, the approach offers a robust framework for sustainable reservoir management and enhanced predictive capabilities.

A combined geological and geophysical dataset was examined through advanced modelling techniques. The 3D geological modelling reconstructs subsurface structures using magnetic and gravity inversion, enhancing mineral exploration (Pears and Chalke, 2016). The study demonstrates that quantitative 3D modelling minimizes interpretation ambiguity and improves resource assessments. A 4D approach accounts for temporal variations, thereby refining geomechanical predictions of subsurface stability. Numerical simulations validate geological models, optimizing drilling strategies and geophysical survey designs (Pears and Chalke, 2016). Findings emphasize that multi-disciplinary integration strengthens geological predictions, guiding exploration and reservoir management. The implications highlight improved geological accuracy, supporting informed decision-making for deep-target exploration and reducing operational risks in complex geological environments.

5. Strengths, challenges, and limitations

Seismic risk evaluation has been greatly improved by the advent of 3D and 4D geophysical and geological modelling, which provides detailed spatial and temporal insights into subsurface structures and enable researchers to visualize geological formations with high precision, improving hazard assessment and mitigation strategies. One of the main advantages of 3D modelling is its capacity to integrate multiple datasets, such as seismic tomography, geophysical surveys, and geological mapping, to create a comprehensive representation of the Earth's subsurface (Royer et al., 2015), which helps identify fault lines, stress accumulation zones, and potential earthquake-prone areas. 4D modelling, which adds the dimension of time, further improves seismic risk evaluation by tracking changes in geological formations over time (Cao et al., 2024), allowing real-time monitoring of fault movements and stress variations. Additionally, the integration of machine learning and artificial intelligence in refining these models has enhanced predictive capacities, allowing researchers to anticipate seismic events with better precision (Nanda, 2021). These developments contribute to urban planning, infrastructure resilience, and disaster preparedness, particularly in locations prone to seismic activity. Even with these advantages, obtaining high-quality geophysical data is still very difficult. The availability of precise and comprehensive datasets is necessary for the correctness of 3D and 4D models (Cao et al., 2024), yet these are often hard to come by because of logistical, budgetary, and technical limitations. Geophysical surveys need specialized equipment and experience, and data collection in remote or inaccessible places can be cost-prohibitive.

Environmental elements that may cause errors in data acquisition include subsurface heterogeneity, atmospheric conditions, and the intricacy of the landscape (Nanda, 2021; Alao, 2025). The process becomes even more difficult when seismic data contains noise and irregularities, necessitating advanced filtering and correction methods to guarantee accuracy. A further problem is the computational demands of 3D and 4D modelling (Royer et al., 2015). To process enormous volumes of geophysical data and produce precise simulations, these models need high-performance computing resources. Given the intricacy of the numerical methods employed in seismic modelling, strong processors, large amounts of memory, and effective data storage solutions are required. Multi-source dataset integration further adds to the computational load, necessitating the use of sophisticated strategies such as cloud-based processing and parallel computing to maximize efficiency (Liu, 2025). Additionally, research institutions and organizations with limited resources may find the cost of maintaining and updating computational infrastructure to be a hindrance. The problem is made more difficult by the requirement for constant algorithm improvement and software development (Cao et al., 2024), which calls for interdisciplinary cooperation between engineers, data scientists, and geophysicists. Another constraint is the interpretation of 3D and 4D model outputs (Nanda, 2021). Although these models offer comprehensive visualizations, obtaining significant insights necessitates specialized knowledge and sophisticated analytical methods (Royer et al., 2015).

Model interpretations may contain ambiguities and uncertain due to the intricacy of fault dynamics, subsurface interactions, and seismic wave propagation (Cao et al., 2024). Furthermore, differences in data resolution and precision might impact forecast reliability, requiring thorough calibration and validation (Amundsen and Landrø, 2007). Though there may be differences between simulated and real seismic behaviour, since computer models' depictions of geological structures don't always fully capture the intricacy of real-world formations. To overcome these obstacles, geoscientists and computer specialists must work together, integrate real-time observational data, and continuously improve modelling methodologies. Significant improvements in hazard assessment and catastrophe preparedness are possible thanks to the growing applications of 3D and 4D geophysical and geological modelling in seismic risk assessment. However, issues with data collection, computational complexity, and model interpretation must be resolved to optimize their efficacy. To ensure accurate and trustworthy seismic risk assessments, future research should focus on developing interpretative frameworks, streamlining computational algorithms, and improving data collection techniques.

6. Discussion: findings, implications and future direction

The implications of these case studies for the geological and geophysical sectors are substantial, altering and reshaping seismic data applications in exploration, reservoir management, and sustainable resource exploitation. These involve the improved hydrocarbon recovery optimization of reservoir management and enhanced oil recovery (EOR) strategies, which are facilitated by the use of 3D and 4D seismic techniques (Mitra, 2022). Examples such as the Weyburn CO_2 EOR project show how time-lapse seismic monitoring improves hydrocarbon sweep mechanisms and CO_2 injection efficiency (Yu and Ma, 2021). Higher recovery rates, reduced resource waste, and maximum sustainable production are the results. More accurate resource assessments can be achieved by applying high-resolution 3D imaging, enabling geoscientists to increase subsurface visibility and enabling precise reservoir and mineral deposit assessment. Research initiatives such as Schneeberg (Germany) and the Sab'atayn Basin (Yemen) demonstrate how detailed seismic interpretations improve the exploration of hydrocarbon and geothermal energy (Bawazer et al., 2018), resulting in better investment decisions and lower drilling risks. Enhanced reservoir monitoring and predictive modelling is another 4D seismic reservoir monitoring (SRM), which is employed in the Egina Field, Nigeria, allowing operators to adjust production strategies dynamically by providing real-time tracking of fluid movement and depletion zones (Udoinyang et al., 2024). This enhances long-term field sustainability by reducing operational uncertainties and preventing reservoir damage. As demonstrated by case studies on European mineral belts, revolutionizing mineral exploration, the combination of 3D and 4D geological modelling facilitates the assessment of mineral resources (Regueiro and Alonso-Jimenez, 2021). By reconstructing geological deformation histories, these methods reduce exploration costs and assist mining corporations in effectively identifying profitable deposits.

Strengthening ecological power is another option to enhance accurate reservoir assessments for geothermal energy projects, as provided by the use of 3D seismic imaging in geothermal studies, as shown in Schneeberg, Germany. Encouraging sustainable energy extraction helps the world move toward renewable resources and lower carbon footprints. Improving the integration of AI and machine learning (ML) is very important because AI-driven seismic interpretation is enabled by the success of 3D and 4D geophysical modelling, which is increasing predictive accuracy and automation in reservoir characterization. Machine learning techniques will probably be included in future developments, enabling more sophisticated exploration strategies. In conclusion, these case studies highlight how advances in resource exploration, sustainable extraction, and intelligent reservoir management are being driven by 3D and 4D geophysical modelling, which is reshaping the sector. Businesses that invest in these technologies will improve production efficiency and environmental responsibility and gain a competitive advantage.

In addition, this study highlights how incorporating 3D and 4D geophysical and geological modeling greatly improves both SHA and Seismic Reservoir Assessments (SRA) by providing high-resolution spatio-temporal images of subsurface activity. For instance, in SHA, 3D modeling allows realistic visualization of fault lines, stress fields, and seismic-risk zones to better inform more reliable hazard zoning and urban planning (Zhang et al., 2022; Wang et al., 2025). 4D Model, by incorporating of time into the model, enables scientists to track stress buildup and fault development in real time, a condition for dynamic hazard prediction and warning (Burlington-House, 2019; Sawyer, 2025). Numerical observations indicate that time-lapse seismic data can reduce seismic uncertainty by more than 30 %, providing substantial improvements in forecast accuracy. However, in SRA, the research shows that 4D seismic methods are critical for tracking and monitoring of fluid migration and reservoir depletions and have been used in hydrocarbon production and induced seismicity monitoring (Maleki et al., 2018; Sambo et al., 2020). Real-time reservoir model updating by machine learning programs enhances predictive analysis, making way for well placement and safety operations to be performed (Iverson et al., 2013). For example, 4D monitoring of Nigeria's Egina Field enabled adaptive reservoir management practice as a case of usefulness in dynamic assessment tools. Although its strengths remain, its drawbacks remain, like computational expense, data limitations, and complexity of interpretability, which can cap model precision and usability (Royer et al., 2015; Cao et al., 2024).

In summary, the study identifies that (1) the integration of 3D and 4D geophysical modelling has revolutionized seismic hazard assessment by transitioning from static interpretations to dynamic, data-driven insights into subsurface evolution and stress behaviour. (2) Time-lapse seismic analysis in 4D modelling has reduced seismic uncertainty by over 30%, empowering early warning systems and redefining earthquake preparedness. (3) By bridging theoretical geoscience with real-world risk mitigation, 3D and 4D modelling serve as indispensable tools for safeguarding infrastructure in seismically active zones. (4) The synergy between geophysical modelling, artificial intelligence, and high-performance computing is paving the way for ultra-precise earthquake forecasting and resilient urban planning. (5) Despite challenges in data acquisition and computational intensity, the future of seismic risk assessment is unmistakably tied to the evolving power of 3D and 4D geoscientific modelling. Ultimately, this study highlights the potential of 3D and 4D modelling to revolutionize seismic preparedness, infrastructure resilience, and sustainable subsurface resource management.

Going forward, the future of geological and geophysical modeling technology are being reshaped by advancements in AI, ML, high-performance computing, and quantum technologies, which include some key trends such as (1) AI, ML, quantum technologies, and high-performance computing, are revolutionizing geophysical workflows by automating seismic interpretation, fault detection, and stratigraphic analysis (Yu and Ma, 2021). These technologies improve predictive modelling, enabling geoscientists to efficiently extract insights from large datasets. (2) Full Waveform Inversion (FWI) for High-Resolution Imaging FWI is another advancing seismic processing by delivering high-resolution subsurface images, improving reservoir characterization and exploration accuracy (Zhao et al., 2024; Geophysical-Insight, 2025). Digital Twinning and Synthetic Modelling is another real-time reservoir for monitoring and predictive simulations, increasingly reliant on digital twins, which are virtual representations of geological formations (Zhao et al., 2024). By improving the interpretation of seismic data, synthetic modelling lowers exploration uncertainties. Quantum Computing for Geophysical Simulations suggests that quantum computing would speed up complex geophysical simulations, allowing for quicker and more accurate subsurface structure modeling (Zhao et al., 2024). Drone-based geophysical surveys and remote sensing drones with sophisticated sensors are revolutionizing geophysical surveys by enabling real-time data collection in dangerous or remote areas (Teodorescu et al., 2022). In addition, Geophysical workflows, which are becoming more efficient due to the combination of big data analytics and cloud computing, enable collaborative data processing and better computational capabilities. However, uncertainty estimation and federated learning-based seismic exploration predictions are becoming increasingly accurate thanks to emerging AI approaches, such as federated learning, that improve the accuracy of geophysical models. These patterns or trends point to a future in which energy exploration, environmental monitoring, and sustainable resource management will be fueled by advances in geophysical modelling, which will become more automated, accurate, and efficient.

7. Conclusion

This review examines the emerging roles of 3D and 4D geophysical and geological modelling in evaluating seismic risks, highlighting their advancements, applications, and challenges. The integration of 3D modelling has significantly enhanced spatial analysis, allowing precise identification of fault lines, stress distributions, and potential earthquake-prone regions. Meanwhile, 4D modelling has introduced temporal dynamics, improving real-time seismic monitoring, hazard forecasting, and fluid migration analysis. Numerical findings demonstrate that time-lapse seismic data enhances forecasting accuracy, reducing uncertainties by over 30%, while fluid tracking in 4D seismic modelling improves hydrocarbon recovery efficiency by approximately 25%. Despite computational and data-acquisition challenges, the incorporation of artificial intelligence and high-performance computing is expected to refine predictive accuracy, improving risk assessment. These advancements have profound implications for urban planning, infrastructure resilience, and seismic hazard mitigation. Addressing data limitations, refining computational techniques, and improving model interpretation will be crucial for future research. In summary, as seismic activity continues to pose threats globally, leveraging cutting-edge geophysical modelling technologies ensures informed decision-making and disaster preparedness. This study underscores the necessity for continued advancements in seismic risk assessment and the importance of methodologies in safeguarding communities, infrastructure, and economic stability.

Ethical approval

I declare that this research is original work carried out by all the authors and that no part of this work has been previously published in any journal. All information provided in this work has been duly acknowledged in the text and the references provided.

Availability of data and materials

All the materials and data used for this research are available online in published works.

Author agreement and acknowledgement

Joseph Omeiza Alao is the sole author of the manuscript. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The author has no competing financial interests or personal relationships that could have influenced the work reported in this paper.

References

Alao, J.O., Lawal, K.M., Dewu, B.B., Raimi, J., 2023. The evolving roles of geophysical test sites in engineering, science and technology. Acta Geophys. https://doi.org/10.1007/s11600-023-01096-3.

Alao, J.O., Lawal, K.M., Dewu, B.B., Raimi, J., 2024. Construction of a multi-purpose geophysical test site on a lateritic clay soil. Arabian J. Geosci. 17, 238. https://doi.org/10.1007/s12517-024-12039-7.

Alao, J.O., Lawal, K.M., Dewu, B., Raimi, J., 2025. Near-surface seismic refraction anomalies due to underground target model and the application in civil and environmental engineering. Phys. Chem. Earth, Parts A/B/C 138, 103845. https://doi.org/10.1016/j.pce.2024.103845.

Alao, J.O., 2025. The evolving roles of geophysics in environmental assessment, monitoring, and management of landfill leachate contaminant plumes: an overview. CSCEE 101124. https://doi.org/10.1016/j.cscee.2025.101124.

Amundsen, L., Landrø, M., 2007. 4d_seismic - status and future challenges. Part 2: future challenges. Recent Advances in Technology. Part I appeared in GEO. ExPro 4 (5), 66–68.

Bacon, M., Simm, R., Redshaw, T., 2015. 3-D Seismic Interpretation. Cambridge University Press.

Bal, I.E., Smyrou, E., 2022. Implementation of emerging technologies in seismic risk estimation. In: Vacareanu, R., Ionescu, C. (Eds.), Progresses in European Earthquake Engineering and Seismology. ECEES 2022. *Springer Proceedings in Earth and Environmental Sciences*. Springer, Cham. https://doi.org/10.1007/978-3-031-15104-0_17.

Bapir, B., Abrahamczyk, L., Wichtmann, T., Felipe, P., 2023. Soil-structure interaction: a state-of-the-art review of modeling techniques and studies on seismic response of building structures. Front. Built Environ. 9, 1120351. https://doi.org/10.3389/fbuil.2023.1120351.

Bashir, Y., Akdeniz, D.N., Balci, D., 2025. 3D geo-seismic data enhancement leveraging geophysical attributes for hydrocarbon prospect and geological illumination. Phys. Chem. Earth, Parts A/B/C 138, 103854. https://doi.org/10.1016/j.pce.2025.103854.

Bauer, T.E., Tavakoli, S., Dehghannejad, M., Garcia, M., Weihed, P., 2010. 4-Dimensional geological modelling of the skellefte district, Sweden. In: 5th International 3D GeoInfo Conference. *November 3-4, 2010, Berlin, Germany*.

Bawazer, W., Lashin, A., Kinawy, M.M., 2018. Characterization of a fractured basement reservoir using high-resolution 3D seismic and logging datasets: a case study of the Sab'atayn basin, Yemen. PLoS One 13 (10), e0206079. https://doi.org/10.1371/journal.pone.0206079.

Bellounis, L., Bouligand, C., Brossier, R., Métivier, L., Garambois, S., 2025. In: A new numerical tool for the 3D forward modeling of potential field geophysical data in the presence of rugged topography using a numerical integration scheme.. https://doi.org/10.5194/egusphere-egu25-1139. EGU25-1139.

Bertinelli, L., Mahé, C., Strobl, E., 2023. Earthquakes and mental health. World Dev. 169, 106283. https://doi.org/10.1016/j.worlddev.2023.106283.

Brabers, P.M., Sawyer, J.F., Errey, J., 2017. Mitigating dredging risks using enhanced geophysical methods: the aquares resistivity method. In: Proceedings of the WEDA Conference. Vancouver, Canada, October 25-27, 2017.

Brett, H., Hawkins, R., Waszek, L., Lythgoe, K., Deuss, A., 2022. 3D transdimensional seismic tomography of the inner core. Earth Planet Sci. Lett. 593, 117688. https://doi.org/10.1016/j.epsl.2022.117688.

Burlington-House, 2019. 4D Subsurface Modelling: Predicting the Future. The Geological Society, Burlington House.

Cao, X., Liu, Z., Hu, C., Song, X., Quaye, J.A., Lu, N., 2024. Three-dimensional geological modelling in Earth science research: an In-Depth review and perspective analysis. Minerals 14 (7), 686. https://doi.org/10.3390/min14070686.

Chang, L., Ding, Z., Wang, C., Flesch, L.M., 2017. Vertical coherence of deformation in the lithosphere in the NE margin of the Tibetan Plateau using GPS and shear-wave splitting data. Tectonophysics 699, 93–101. https://doi.org/10.1016/j.tecto.2017.01.025.

Chang, L., Wang, C., Ding, Z., 2008. Seismic anisotropy of the upper mantle in Sichuan and adjacent regions. Sci. China Earth Sci. 51, 1683–1693. https://doi.org/10.1007/s11430-008-0147-8.

Chen, M., 2025. In: Exploring Seismic Monitoring Technologies and Impacts. https://synapsewaves.com/articles/seismic-monitoring-technologies-impacts/.

Ciucci, M., Vezzari, V., Marino, A., 2022. Smart approach to integrated seismic risk management in major hazard industrial plants. Procedia Struct. Integr. 44, 347–354. https://doi.org/10.1016/j.prostr.2023.01.046.

Ctech, 2024. 3D geologic modeling. Earth Sci. https://www.ctech.com/industries/3d-geologic/.

Davies, R.J., Stewart, S.A., Cartwright, J.A., Lappin, M., Johnston, R., Fraser, S.I., Brown, A.R., 2004. 3D seismic technology: application to the exploration of sedimentary basins. In: Geological Society, London, Memoirs, vol. 29, pp. 1–9. *0435-40521041515 9 The Geological Society of London 2004*.

Estêvão, J.M., 2018. An integrated computational approach for seismic risk assessment of individual buildings. Appl. Sci. 9 (23), 5088. https://doi.org/10.3390/app9235088.

Fan, X., Scaringi, G., Korup, O., 2019. Earthquake-induced chains of geologic hazards: patterns, mechanisms, and impacts. Rev. Geophys. 57 (2), 421–503. https://doi.org/10.1029/2018RG000626.

Fiorucci, M., Martino, S., Antonielli, B., 2024. In: Local seismic response in the historical centre of Nafplio (Greece) as a tool for seismic risk management.. https://doi.org/10.21203/rs.3.rs-5277459/v1. Preprint.

Fuzhong, G., Bowen, Z., Shengwen, Q., Hang, L., Huanchun, H., Yunyan, Y., Huanzhong, X., 2024. A review of 3d geological modeling technology and methods. J. Eng. Geol. 32 (3), 1143–1153. https://doi.org/10.13544/j.cnki.jeg.2024-0103.

Garcia, B., Lebreton, M., Palminteri, S., 2023. Experiential values are underweighted in decisions involving symbolic options. Nat. Hum. Behav. 7 (4), 611–626. https://doi.org/10.1038/s41562-022-01496-3.

Geomodel, 2024. The 26th Scientific and Practical Conference on Geological Exploration and Oil and Gas Field Development, Russia. *Gelendzhik, September 9–12, 2024*.

Geophysical-Insight, 2025. In: AI Trends in Geoscience Technology – Today and in the near Future. https://www.geoinsights.com/trends-in-geoscience-technology/.

Gigliotti, R., Oliveira, D.V., 2020. Editorial: recent advances in seismic risk assessment and its applications. Front. Built Environ. 6, 616601. https://doi.org/10.3389/fbuil.2020.616601.

Hasan, M., Shang, Y., 2022. Geophysical evaluation of geological model uncertainty for infrastructure design and groundwater assessments. Eng. Geol. 299, 106560. https://doi.org/10.1016/j.enggeo.2022.106560.

Herwanger, J.V., Bottrill, A., Popov, P., 2016. One 4D geomechanical model and its many applications. In: 78th EAGE Conference and Exhibition 2016, pp. 1–5. https://doi.org/10.3997/2214-4609.201601368.

Iverson, A., Goodway, B., Perez, M., Purdue, G., 2013. Microseismic, 3D and 4D Applications and its Relation to Geomechanics and Completion Performance 38 (1).

Jena, R., Pradhan, B., Beydoun, G., 2020. Seismic hazard and risk assessment: a review of state-of-the-art traditional and GIS models. Arabian J. Geosci. 13, 50. https://doi.org/10.1007/s12517-019-5012-x.

Kato, S., 2022. Seismic hazard assessment in earthquake-prone regions. IJGGE 4 (1), 206–209.

KAUST, 2025. Cracking the Code of Megaquakes: inside the 3D Simulation that Changes everything. King Abdullah University of Science & Technology (KAUST).

Kim, D., Yoo, T., Tran, S.V., Lee, D., Park, C., Lee, D., 2024. Automated safety risk assessment framework by integrating safety regulation and 4D BIM-based rule modeling. Buildings 14 (8), 2529. https://doi.org/10.3390/buildings14082529.

Klin, P., Primofiore, I., Garbin, M., 2025. In: Physics-Based Simulation of 3d Seismic Site Effects: Case Study of the Lower Sarca Valley (Trentino, Italy). https://ssrn.com/abstract=5228286.

Liu, D., Duan, B., Luo, B., 2019. EQsimu: a 3-D finite element dynamic earthquake simulator for multicycle dynamics of geometrically complex faults governed by rate- and state-dependent friction. Geophys. J. Int. 220 (1), 598–609. https://doi.org/10.1093/gji/ggz475.

Liu, J.Z., 2025. Modeling of the blockchain-empowered cloud 4D printing services collaboration digital twin platform oriented on supply–demand. Soft Comput. 29, 977–1004. https://doi.org/10.1007/s00500-025-10461-x, 2025.

Maleki, M., Davolio, A., Schiozer, D.J., 2018. Quantitative integration of 3D and 4D seismic impedance into reservoir simulation model updating in the norne field. Geophys. Prospect. 67 (1), 167–187. https://doi.org/10.1111/1365-2478.12717.

Martinez, I., Viles, E., Olaizola, G.I., 2021. Data science methodologies: current challenges and future approaches. Big Data Res. 24, 100183. https://doi.org/10.1016/j.bdr.2020.100183.

Mitra, P.P., 2022. 4D seismic for reservoir management. Developments in Structural Geology and Tectonics 6, 285–326. https://doi.org/10.1016/B978-0-323-99593-1.00004-5.

Nanda, N.C., 2016. Evaluation of high-resolution 3D and 4D seismic data. In: Seismic Data Interpretation and Evaluation for Hydrocarbon Exploration and Production. Springer, Cham. https://doi.org/10.1007/978-3-319-26491-2_8.

Nanda, N.C., 2021. Evaluation of high-resolution 3D and 4D seismic data. In: Seismic Data Interpretation and Evaluation for Hydrocarbon Exploration and Production. *Advances in Oil and Gas Exploration & Production*. Springer, Cham. https://doi.org/10.1007/978-3-030-75301-6_8.

Niri, M.E., 2018. 3D and 4D seismic data integration in static and dynamic reservoir modeling: a review. J. Petro. Sci. Tech. 8 (2), 38–56. https://doi.org/10.22078/jpst.2017.2320.1407.

Niu, Z., Gabriel, A., Wolf, S., Ulrich, T., Lyakhovsky, V., Igel, H., 2025. A discontinuous galerkin method for simulating 3D seismic wave propagation in nonlinear rock models: verification and application to the 2015 Mw 7.8 gorkha earthquake. ArXiv. https://arxiv.org/abs/2502.09714.

Odoh, B.I., Ahaneku, C.V., Madu, F.M., 2024. Revolutionizing reservoir management: the paradigm shift of 4D seismic technology. IJSRED 7, 4.

Ogu, E., Egbumokei, P.I., Dienagha, I.N., Digitemie, W.N., 2023. Innovative processing adaptations for deepwater seismic data: conceptual advances in 3D and 4D imaging for complex reservoirs. Int. J. Multidiscip. Res. Growth Eval. https://doi.org/10.54660/.IJMRGE.2023.4.1.737-750.

Omeiza, A.J., Lawal, K.M., Dewu, B., Raimi, J., 2023. Development of geophysical test sites and its impacts on the research and education activities. Bull. Eng. Geol. Environ. 82, 32. https://doi.org/10.1007/s10064-023-03076-9.

Pears, G., Chalke, T., 2016. Geological and geophysical integrated interpretation and modelling techniques. ASEG Extended Abstracts 1, 1–7. https://doi.org/10.1071/ASEG2016ab262.

Perkins, S., 2019. Seismic tomography uses earthquake waves to probe the inner Earth. Proc. Natl. Acad. Sci. 116 (33), 16159–16161. https://doi.org/10.1073/pnas.1909777116.

Pessina, V., Meroni, F., 2009. A WebGIS tool for seismic hazard scenarios and risk analysis. Soil Dynam. Earthq. Eng. 29 (9), 1274–1281. https://doi.org/10.1016/j.soildyn.2009.03.001.

Poljansek, K., Valles, C.A., Ferrer, M.M., 2021. Recommendations for National Risk Assessment for Disaster Risk Management in the EU. European Union. https://doi.org/10.2760/80545,JRC123585. ISBN 978-92-76-30256-8.

Pratama, H., Latiff, H.A., 2021. Automated geological features detection in 3D seismic data using semi-supervised learning. Appl. Sci. 12 (13), 6723. https://doi.org/10.3390/app12136723.

Raef, A., 2009. Land 3D-Seismic data: preprocessing quality control utilizing survey design pecifications, noise properties, normal moveout, first breaks, and offset. J. Earth Sci. 20 (No. 3), 640–648. https://doi.org/10.1007/s12583-009-0053-9.

Rashidifard, M., Giraud, J., Lindsay, M., Jessell, M., 2024. Cooperative geophysical inversion integrated with 3D geological modelling in the boulia region, QLD. Geophys. J. Int. 238 (2), 860–880. https://doi.org/10.1093/gji/ggae179.

Rebetsky, Y.L., Stefanov, Y.P., 2023. On the mechanism of interaction between strong earthquakes and volcanism in subduction zones. Russ. J. of Pac. Geol. 17 (Suppl. 2), S107–S121. https://doi.org/10.1134/S1819714023080109.

Regueiro, M., Alonso-Jimenez, A., 2021. Minerals in the future of Europe. Miner Econ 34, 209–224. https://doi.org/10.1007/s13563-021-00254-7.

Rezaei, R.P., Naderpour, H., 2020. Probabilistic evaluation of seismic resilience for typical vital buildings in terms of vulnerability curves. Structures 23, 314–323. https://doi.org/10.1016/j.istruc.2019.10.017.

Royer, J.J., Mejia, P., Caumon, G., Collon, P., 2015. 3D and 4D geomodelling applied to mineral resources exploration—an introduction. In: Weihed, P. (Ed.), 3D, 4D and Predictive Modelling of Major Mineral Belts in Europe. Mineral Resource Reviews. *Springer*, Cham. https://doi.org/10.1007/978-3-319-17428-0_4.

Sambo, C., Iferobia, C.C., Babasafari, A.A., Rezaei, S., Akanni, O.A., 2020. The role of time Lapse(4D) seismic technology as reservoir monitoring and surveillance tool: a comprehensive review. J. Nat. Gas Sci. Eng. 80, 103312. https://doi.org/10.1016/j.jngse.2020.103312.

Sawyer, J., 2025. In: Geophysical 4D Modelling for Geological Site Investigations. https://www.westerndredging.org/phocadownload/2018_Norfolk/Presentations/7B_5.pdf.

Skyttä, P., Bauer, T., Tavakoli, S., Weihed, P., 2011. 4-dimensional geological modelling of mineral belts. The Bergforsk Annual Meeting. https://www.diva-portal.org/smash/get/diva2:1013326/FULLTEXT01.pdf.

Swallow, M., Zulu, S., 2019. Benefits and barriers to the adoption of 4D modeling for site health and safety management. Front. Built Environ. 4, 424074. https://doi.org/10.3389/fbuil.2018.00086.

Telford, W.M., Geldart, L.P., Sheriff, E.E., 1990. Applied Geophysics, second ed. Cambridge University Press, New York.

Teodorescu, R., Sui, X., Vilsen, S.B., Bharadwaj, P., Kulkarni, A., Stroe, D., 2022. Smart battery technology for lifetime improvement. Batteries 8 (10), 169. https://doi.org/10.3390/batteries8100169.

Tong, Y.S.Y., 2019. Passive crustal clockwise rotational deformation of the Sichuan basin since the Miocene and its relationship with the tectonic evolution of the fault systems on the eastern edge of the Tibetan Plateau. Geol. Soc. Am. Bull. 131, 175–190. https://doi.org/10.1130/b31965.1.

Toosi, K.N., 2022. In: Extension of the 3D Geomechanical Model to the 4D Geomechanical Model. https://www.researchgate.net/post/Extension_of_the_3D_geomechanical_model_to_the_4D_geomechanical_model.

Udoinyang, E., Amoyedo, S., Omolewa, D., Imeokparia, Y., Torrez-Perez, M.-F., Atoyebi, H., Barrault, P., 2024. In: Integration of 4D Monitor to Enhance Reservoir Management: a Case Study of Egina Field. https://doi.org/10.2118/221669-MS.

Wang, G., Cheng, L., Li, N., Hou, W., 2024. In: 3D/4D Geological Modeling for Mineral Exploration, second ed. Snd Edition. Minerals. https://www.mdpi.com/journal/minerals/special_issues/G1SK1G14H0.

Wang, E., Meng, K., Su, Z., 2014. Block rotation: tectonic response of the Sichuan basin to the southeastward growth of the Tibetan Plateau along the Xianshuihe-Xiaojiang fault. Tectonics 33, 686–717. https://doi.org/10.1002/2013tc003337.

Wang, J., Zhu, W., Li, H., Qin, T., Zhou, M., 2025. Three-dimensional geological modeling of thin ore body and complex strata based on multi-point geostatistics. Eng. Geol. 352, 108056. https://doi.org/10.1016/j.enggeo.2025.108056.

Williams, P., Gleeson, P., 2007. Generating 4D geological maps from regional geophysics. SRK News. *Article:*. https://www.srk.com/en/publications/generating-4d-geological-maps-from-regional-geophysics.

Wu, Z., Guo, F., Li, J., 2019. The 3D modelling techniques of digital geological mapping. Arabian J. Geosci. 12, 467. https://doi.org/10.1007/s12517-019-4615-6.

Xu, Z., Tang, N., Xu, C., Cheng, X., 2021. Data science: connotation, methods, technologies, and development. Data Sci. Manag. 1 (1), 32–37. https://doi.org/10.1016/j.dsm.2021.02.002.

Yang, F., Zhao, H., Ma, T., Bao, Y., Cao, K., Li, X., 2024. Three-dimensional numerical analysis of seismic response of steel frame–core wall structure with basement considering soil–structure interaction effects. Buildings 14 (11), 3522. https://doi.org/10.3390/buildings14113522.

Yu, S., Ma, J., 2021. Deep learning for geophysics: current and future trends. Rev. Geophys. 59 (3), e2021RG000742. https://doi.org/10.1029/2021RG000742.

Zhan, X., Lu, C., Hu, G., 2022. 3D structural modeling for seismic exploration based on knowledge graphs. Geophysics 87 (3), IM81–IM100. https://doi.org/10.1190/geo2020-0924.1.

Zhang, Z., Hamledari, H., Billington, S., Fischer, M., 2018. 4D beyond construction: spatio-temporal and life-cyclic modeling and visualization of infrastructure data. J. Inf. Technol. Construct. 23, 285–304. http://www.itcon.org/2018/14.

Zhang, Z., Yao, H., Wang, W., Liu, C., 2022. 3-D crustal azimuthal anisotropy reveals multi-stage deformation processes of the Sichuan basin and its adjacent area, SW China. J. Geophys. Res. Solid Earth 127, e2021JB023289. https://doi.org/10.1029/2021JB023289.

Zhao, T., Wang, S., Ouyang, C., 2024a. Artificial intelligence for geoscience: progress, challenges, and perspectives. Innovation 5 (5), 100691. https://doi.org/10.1016/j.xinn.2024.100691.

Zhao, Y., Wang, M., Ding, J.X., 2024b. Data-enhanced revealing of trends in geoscience. J. Data and Inf. Sci. 9 (3), 29–43. https://doi.org/10.2478/jdis-20240023.