



A REVIEW OF NUMERICAL MODELS FOR PREDICTING SUBSIDENCE IN ABANDONED MINES (2015–2025)

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Abstract: *Subsidence in abandoned mines presents significant geotechnical and environmental risks, threatening infrastructure, ecosystems, and human safety, often decades after mining activities have ceased due to the gradual collapse or deformation of underground voids. This process can result in structural damage, soil degradation, altered groundwater flow, and sinkhole formation. The complexity of subsidence is controlled by the interaction of geological conditions, mining geometry, hydrogeological processes, and the mechanical behaviour of rock masses, which are often inadequately represented by empirical approaches. This review critically evaluates numerical modelling techniques used for subsidence prediction in abandoned mines, with particular emphasis on the Finite Element Method (FEM), Finite Difference Method (FDM), Discrete Element Method (DEM), coupled hydro-mechanical approaches, and monitoring-integrated techniques. FEM and FDM are widely applied for continuum-based stress–strain and deformation analysis, whereas DEM and hybrid FEM–DEM approaches are more suitable for modelling discontinuities, fracture propagation, and caving mechanisms. Coupled hydro-mechanical simulations enhance the understanding of groundwater-related deformation processes, while monitoring-based methods, integrating remote sensing, LiDAR, ERT, and InSAR, improve model calibration and validation. Advanced FEM–DEM models can simulate complex goaf behaviour with errors below 10%, while coupled hydro-mechanical simulations can predict surface uplift of up to 1.2 meters in water-affected areas, supporting more accurate analysis and sustainable management of abandoned mining regions. Studies from Albania demonstrate that integrating slope stability analysis, environmental assessment, and numerical modelling improves the understanding of mining-induced ground deformation. The review identifies major research gaps related to long-term validation, uncertainty in geological parameters, limited integration of monitoring data, and the absence of standardised modelling frameworks. Future research should prioritise hybrid multi-physics modelling, real-time monitoring integration, and standardised risk assessment methodologies to improve the reliability and sustainability of subsidence management in abandoned mining regions.*

Keywords: *Mine subsidence; Numeric modelling; Ground deformation; Abandoned mines; Geotechnical risk assessment; Underground cavity behaviour.*

1. Introduction

Subsidence in abandoned mines is a critical geotechnical and environmental issue that affects both natural landscapes and built infrastructure [1]. It arises from the gradual collapse or deformation of mined-out voids, often decades after mining has ceased. Consequences include structural damage, soil degradation, altered groundwater flow, and sinkhole formation, all of which pose significant risks to human safety and sustainable land use. The complexity of subsidence phenomena stems from the interplay of geomechanical properties of rock and soil, mining methods, geological structures, hydrogeological conditions, and post-mining residual stresses. Traditional empirical and analytical approaches are often insufficient for capturing the non-linear, time-dependent, and site-specific nature of subsidence [2].

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Numerical modelling is a powerful approach for analysing ground displacements and subsidence associated with abandoned mine workings, enabling detailed investigation of complex geological conditions and mining histories that are difficult to capture with purely empirical methods. Researchers commonly apply continuum methods such as the Finite Element Method (FEM) and Finite Difference Method (FDM) to simulate stress–strain behaviour of rock masses and predict surface deformation trends, as well as discontinuum approaches like the Discrete/Distinct Element Method (DEM) to model block interactions and progressive failure mechanisms [3, 4, 5]. These models are often calibrated or validated with observed field data to enhance accuracy and to assess factors influencing subsidence risk, including cavity geometry, rock mass properties, and groundwater effects. Numerical studies in abandoned mine contexts not only improve understanding of displacement processes but also support risk evaluation and mitigation planning for infrastructures affected by post-mining ground movements [6]. Different numerical approaches provide distinct advantages depending on the geological setting and the scale of deformation being investigated. FEM is particularly effective for analysing continuum deformation, stress redistribution, and slope stability in rock masses, whereas FDM is commonly applied to large-scale geotechnical simulations involving progressive deformation and subsidence evolution. In contrast, DEM and hybrid FEM–DEM approaches are better suited for modelling discontinuities, fracture propagation, block interaction, and caving processes in fractured rock masses. The selection of an appropriate modelling technique, therefore, depends on the trade-off between computational efficiency, data availability, and the capability to represent complex hydro-mechanical and discontinuous behaviour.

Residual subsidence models have also gained importance, especially in the context of post-mining settlement analysis and urban infrastructure planning. Furthermore, coupled hydro-mechanical models are increasingly utilised to account for the influence of groundwater and long-term deformation processes. More recently, monitoring-based approaches have emerged, integrating numerical simulations with field data obtained from techniques such as Electrical Resistivity Tomography (ERT) and remote sensing.

Despite significant progress in numerical subsidence modelling, several important research gaps remain. Many studies rely on site-specific assumptions and lack long-term validation using field observations. In addition, the integration of hydrogeological processes with mechanical deformation remains limited in many conventional models, particularly in abandoned mines affected by groundwater rebound. Uncertainty associated with historical mining geometry, fracture development, and rock mass parameters also reduces predictive reliability. Furthermore, while monitoring technologies such as InSAR, LiDAR, ERT, and remote sensing have improved deformation detection, their integration into predictive numerical frameworks is still insufficiently developed.

Research on geohazards and mining-related impacts in Albania has combined slope stability analysis, environmental assessment, and subsidence modelling to understand and mitigate risks. Muceku and Korini (2014) [7] evaluated landslides and slope stability in the historical town of Kruja, emphasising the role of geotechnical assessments for hazard mitigation. Halili and Muka (2016) [8] highlighted environmental issues associated with abandoned mining sites, particularly soil and water contamination, while Korini et al. (2009) [9] investigated rock mass properties and underground tunnel stability, providing insights into safe excavation practices. Focusing on subsidence, Muceku et al. (2019) [10] analysed mining-induced ground deformation in urban and rural areas, assessing geoenvironmental consequences, and Bukaçi and Korini (2017) [11] applied the convergence-confinement numerical method to predict tunnel-induced ground movements. Collectively, these studies demonstrate the integration of field observations, environmental analysis, and predictive numerical modelling to understand, monitor, and manage geohazards in Albania.

This study aims to critically review and analyse existing research on numerical modelling techniques used to investigate ground displacements and subsidence in abandoned mines. Particular attention is given to comparing FEM, FDM, DEM, coupled hydro-mechanical models, and monitoring-integrated approaches in terms of their applicability, strengths, and limitations. The review further identifies key factors controlling subsidence behaviour, highlights current research gaps related to long-term prediction and model validation, and proposes practical recommendations for improving subsidence assessment and risk management in abandoned mining regions.

2. Material and method

This review follows a structured literature synthesis approach to ensure a comprehensive and systematic analysis of existing research. First, in the literature selection phase, studies published between 2015 and 2025 that focus on numerical modelling of subsidence in abandoned mines were considered. From this pool, a total of 17 studies were selected as representative of recent advances in the field.

Second, during data extraction, key information was collected from each study. This included the modelling methods and software used, such as FLAC3D, Ansys Fluent, UDEC, and Itasca. Additionally, important parameters were identified, including rock mass properties, fracture networks, and hydrogeological conditions. The application focus of each study was also examined, covering areas such as goaf stability, sinkhole hazards, and impacts on urban environments. Where applicable, validation methods were noted, particularly the integration of numerical models with monitoring data such as ERT, remote sensing, and in situ measurements. The strengths and limitations reported in each study were also documented.

Finally, in the categorisation and analysis stage, the selected studies were grouped into key methodological categories, including FEM, DEM and hybrid FEM–DEM approaches, residual subsidence models, hydro-mechanical models, and monitoring-integrated approaches. A comparative analysis was then conducted using a summary table that highlights the methods employed, key parameters, as well as the strengths and limitations of each approach.

3. Results

From analysing 17 studies that use numerical modelling to simulate subsidence in abandoned mines, a range of methods with distinct capabilities has been identified, depending on the complexity of geological conditions and research objectives (Figure 1). The approaches include continuum methods such as FEM and FDM, discontinuum techniques like DEM and DDA, and coupled hydro-mechanical and residual subsidence models, each selected based on factors such as rock mass properties, cavity geometry, and groundwater influence.

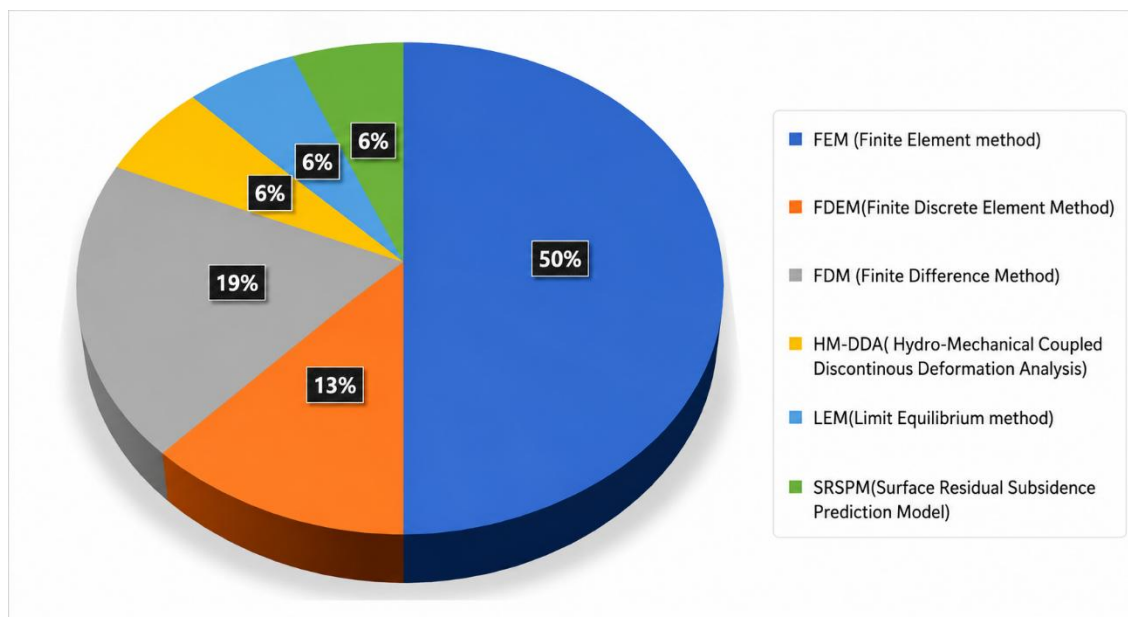


Fig. 1. Numerical modelling approaches used in subsidence studies of abandoned mines

Figure 2 summarises the software platforms employed in these studies, illustrating the diversity of tools used to predict ground deformation and assess subsidence risks.

3.1. Modelling Methods

The majority of studies employ Finite Element Methods to simulate rock mass behaviour, slope stability, and subsidence phenomena. For instance, Jeon et al. (2022) and Shi et al. (2023) applied FEM with enhancements like the Strength Reduction Method (SRM) to model hazard levels and realistic failure prediction, while Guo et al. (2024) used FEM to assess structural interactions in mining goafs [12, 13, 14].

FEM coupled with hydro-mechanical modelling allows integration of water pressure and groundwater effects, capturing long-term stability and hydrogeological impacts, though it is sensitive to water parameters and often site-specific [15, 16, 17].

Another widely used approach is the Finite Discrete Element Method, sometimes combined with Discrete Fracture Networks, as seen in Mai & Li (2023) and Hamdi et al. (2018). This method excels at modelling complex fracture propagation and caving but is computationally intensive [18, 19].

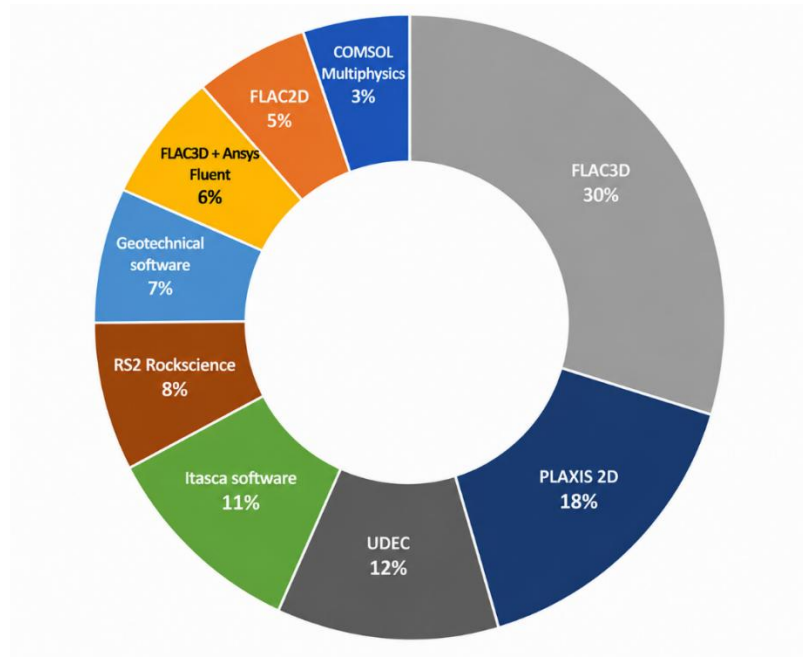


Fig. 2. Summary of numerical modelling software applied across the reviewed studies

Similarly, Finite Difference Methods, often integrated with Electrical Resistivity Tomography, are applied for terrain deformation and sinkhole hazard prediction (Ścigała et al., 2023), though simplifications can reduce accuracy [20].

Specialised techniques include Hydro-Mechanical Coupled Discontinuous Deformation Analysis (HM-DDA) in UDEC (Gao et al., 2024) for precise modelling of fractured formations and seepage, Surface Residual Subsidence Prediction Models (SRSPM) for post-mining subsidence (Guo et al., 2021), and Limit Equilibrium Methods (LEM) combined with InSAR for integrating terrain monitoring data (Wei et al., 2018) [21, 22, 23]. Emerging approaches also utilise LiDAR with FEM (Trigueros et al., 2024) to evaluate backfilling effectiveness [24].

Overall, FEM and FDEM dominate geotechnical modelling due to their flexibility in simulating rock mass behaviour and mining-induced deformations. The choice of method depends on the trade-off between accuracy, computational cost, data availability, and the ability to capture hydro-mechanical interactions and fracture networks.

3.2. Key Parameters

Accurate prediction of subsidence in abandoned mines depends on a range of critical parameters that define both the mechanical behaviour of the rock mass and the surrounding environmental conditions.

Rock mass properties play a fundamental role, particularly factors such as plasticity, cohesion, and strain-softening behaviour, which directly influence deformation and failure mechanisms within the subsurface [12, 13, 25].

Mining-related factors are also essential, including the geometry of excavations, the layout of goaf areas, and the history of mineral extraction. These elements determine the distribution of voids and stress redistribution patterns that contribute to subsidence [16, 22, 24, 26].

Hydrogeological conditions, especially groundwater flow, significantly affect long-term stability. Changes in pore pressure and water-rock interactions can accelerate deformation processes, making coupled hydro-mechanical considerations important [15, 16, 17].

Additionally, the presence and evolution of fracture networks, along with block interactions and caving processes, are key parameters in discontinuous media. These factors control how the rock mass breaks, moves, and ultimately contributes to surface subsidence [18, 19, 21].

3.3. Validation and Accuracy

Ensuring the reliability of subsidence predictions requires rigorous validation and careful calibration of numerical models, as clearly demonstrated by the studies summarised in the table 1. Several approaches emphasise the importance of validating model outputs against real-world monitoring data, such as the FEM-based analysis validated with field measurements [20, 23, 27].

At the same time, many models are highly sensitive to input parameters, particularly in coupled hydro-mechanical simulations where groundwater conditions significantly influence results [15, 16, 17]. The need for careful calibration is further reinforced by the reliance on site-specific geological conditions and historical mining data in studies [22, 26]. Moreover, advanced numerical techniques like FDEM and DFN, while capable of capturing complex fracture and caving processes, are data-intensive and computationally demanding, increasing the importance of accurate parameter calibration [18, 19].

Overall, these studies highlight that without systematic validation and well-constrained input parameters, even sophisticated models may yield unreliable predictions, underscoring the critical role of calibration and validation in subsidence modelling.

4. Comparative Analysis of Numerical Models

Table 1 provides a comprehensive overview of all analysed studies, detailing the numerical methods, software, and the strengths and limitations of each approach. This compilation enables comparison across methodologies, highlights trends in modelling strategies, and identifies areas where further development is needed. Collectively, these results provide a solid foundation for selecting appropriate numerical modelling approaches in future research and practical subsidence risk management, particularly in regions with complex mining histories.

Table 1. Summary of analysed studies, including methods, software, strengths, and limitations

Reference	Method	Software Approach	Key Parameters	Strengths	Limitations
[Jeon et al., 2022]	FEM (Finite Element method) + SRM (Strength Reduction Method)	FLAC2D	Rock mass properties, strength factor, cavity geometry	Accurate hazard level model	High computational cost
[Mai & Li, 2023]	FDEM (Finite Discrete Element Method)	Itasca software	Fracture networks, repeated mining	Captures caving and fracture propagation	Data-intensive
[Hamdi et al., 2018]	FDEM (Finite Discrete Element Method) + DFN (Discrete Fracture Network)	Itasca software	Rock block behaviour, fracture connectivity	Models complex caving	Computationally heavy
[Weber & Konietzky, 2025]	FEM (Finite Element method) + Coupled Hydro-Mechanical	FLAC3D + Ansys Fluent	Water pressure, rock mass behaviour	Long-term stability prediction	Sensitive to hydro parameters
[Bekendam, 2020]	FEM (Finite Element method)	PLAXIS 2D	Mine geometry, historical collapse	Retroactive hazard analysis	Requires historical data
[Renaud et al., 2021]	FEM (Finite Element method) + Coupled Hydro-Mechanical	PLAXIS 2D	Slope geometry, rock properties	Integrates risk assessment	Site-specific
[Vervoort, 2022]	FEM+ Coupled Hydro-Mechanical	PLAXIS 2D	Groundwater conditions, surface uplift	Captures hydrogeological effects	Dependent on water parameter accuracy
[Shi et al., 2023]	FEM (Finite Element method)	FLAC3D	Strain-softening rock properties	Realistic failure prediction	Requires detailed constitutive modelling
[Sikora & Wesołowski, 2021]	FDM (Finite Difference Method)	FLAC3D	Rock plasticity, previous mining	Evaluates terrain deformations	Simplifications may reduce accuracy
[Gao et al., 2024]	HM-DDA (Hydro-Mechanical Coupled Discontinuous Deformation Analysis)	UDEC	Fractured formations, seepage	Models fractures accurately	High computational cost
[He et al., 2023]	FEM (Finite Element method) / Validation	COMSOL Multiphysics	Goaf morphology, surface subsidence	Validated with monitoring data	Site-specific
[Guo et al., 2021]	SRSPM (Surface Residual Subsidence Prediction Model)	UDEC	Goaf geometry, residual deformation	Predicts post-mining subsidence	Needs historical mining data

Reference	Method	Software Approach	Key Parameters	Strengths	Limitations
[Guo et al., 2024]	FEM (Finite Element method)	FLAC3D	Beam response, goaf deformation	Assesses structure interaction	Requires detailed residual data
[Liu et al., 2023]	FDM (Finite Difference Method)	FLAC3D	Surface deformation, building interaction	Predicts impact on structures	Site-specific, parameter sensitivity
[Ścigała et al., 2023]	FDM (Finite Difference Method) + ERT (Electrical Resistivity Tomography)	FLAC3D	Subsurface resistivity, sinkhole hazard	Combines monitoring and modelling	Requires ERT data
[Trigueros et al., 2024]	FEM (Finite Element method) + LiDAR	RS2 Rockscience	Backfilling, goaf stability	Evaluates backfilling effectiveness	Needs accurate backfill parameters
[Wei et al., 2018]	LEM (Limit Equilibrium method) + InSAR	Geotechnical software	Terrain deformation, material properties	Integrates monitoring data	Limited by resolution

5. Discussion

Recent research on subsidence modelling in abandoned mines reveals several important trends, alongside the strengths, limitations, and ongoing challenges associated with different approaches. In terms of trends, there is a growing adoption of hybrid FEM–DEM models, particularly for simulating fracture development and caving processes with greater realism. At the same time, coupled hydro-mechanical models are increasingly being used to incorporate groundwater effects and better represent long-term subsurface behaviour [15, 17]. Residual subsidence models are also gaining prominence, especially in applications related to urban infrastructure and post-mining risk assessment [14, 22]. Furthermore, the integration of monitoring data and remote sensing techniques has become more common, significantly improving model validation and predictive accuracy [20, 23].

Each modelling approach offers distinct capabilities depending on whether the problem involves continuum deformation, discontinuous fracture behaviour, groundwater coupling, or monitoring-based validation. FEM provide accurate continuum modelling but is often associated with high computational demands [12, 13]. In contrast, DEM and hybrid FEM–DEM approaches are well-suited for capturing discontinuities and caving processes, although they require detailed fracture data to be effective [18, 19, 21]. Residual subsidence models are particularly useful for long-term planning in urban areas, but their accuracy depends heavily on the availability and quality of historical and site-specific data [14, 22]. Coupled hydro-mechanical models allow for the inclusion of groundwater effects, yet they require precise hydrogeological inputs, which can be difficult to obtain [15, 17]. Monitoring-based approaches improve overall model accuracy through validation with real-world data, but their effectiveness is limited by data availability and quality [23, 24, 28].

Despite these advancements, several challenges remain. There is still a lack of standardised methodologies applicable across different types of mines, making comparisons and generalisations difficult. Accurately capturing long-term, post-mining residual subsidence continues to be a complex task [14, 22]. In addition, large-scale simulations are often constrained by computational limitations. Finally, the integration of artificial intelligence and real-time monitoring systems into subsidence modelling remains limited, representing an important area for future research and development.

6. Conclusions

Numerical modelling plays a crucial role in predicting subsidence in abandoned mines, providing essential support for risk assessment, mitigation strategies, and land-use planning. Among the available approaches, FEM, hybrid FEM–DEM techniques, and DDA have proven effective in simulating stress distribution, deformation, caving processes, and fracture propagation within rock masses. Coupled hydro-mechanical models and residual subsidence models are particularly valuable for analysing long-term behaviour and post-mining stability, capturing the influence of groundwater and the gradual settlement processes that continue long after mining operations cease.

The integration of monitoring data, including remote sensing and in situ measurements, further enhances the reliability and credibility of numerical simulations. These methods allow models to be calibrated and validated against observed ground movements, improving prediction accuracy and informing practical interventions.

In practical applications, combining numerical simulations with real-time monitoring and hydro-mechanical coupling offers the most reliable framework for long-term subsidence prediction and infrastructure risk management in abandoned mining environments.

For Albania, where abandoned mining sites are numerous and often overlap with urban areas or agricultural lands, applying these numerical modelling techniques is critical. They provide a scientific basis for assessing subsidence risk, guiding infrastructure development, and prioritising remediation efforts. This study highlights the potential for combining advanced modelling, field monitoring, and site-specific data to support sustainable post-mining land management in Albania. Future research should prioritise integrating real-time monitoring systems, advancing multi-scale modelling approaches, and developing national guidelines for standardised subsidence assessment, thereby supporting safer, more reliable, and resilient planning in mining-affected regions.

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