Metaheuristic and AI-Driven Optimization in Earthquake Engineering: A Systematic Review of Algorithms, Applications, and Future Directions

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Abstract

The increasing frequency and severity of seismic events worldwide demand innovative and adaptive solutions in earthquake engineering, early warning, and emergency response systems. Traditional deterministic optimization techniques often fall short in addressing the high-dimensional, nonlinear, and data-uncertain nature of many seismic problems. In contrast, metaheuristic algorithms—stochastic, population-based search methods inspired by natural phenomena—have emerged as powerful alternatives capable of providing robust and near-optimal solutions in complex environments. This review synthesizes the growing body of research on the application of metaheuristic optimization techniques across diverse earthquake-related domains. We examine over fifty influential studies that employ algorithms such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Differential Evolution (DE), Ant Colony Optimization (ACO), Grey Wolf Optimization (GWO), and modern hybrid and multi-objective approaches. Applications span a wide spectrum—from seismic source localization and structural design, to tuned mass damper configuration, sensor placement, earthquake classification, and real-time emergency resource allocation. The review identifies key trends, including the evolution from single-algorithm methods to hybrid models that combine the strengths of multiple metaheuristics, and the transition from static to dynamic, real-time optimization frameworks. Addi-tionally, the integration of machine learning and reinforcement learning with metaheuristic search is shown to significantly improve the adaptability, accuracy, and performance of seismic systems. For instance, PSO-optimized neural networks and GA-tuned support vector machines have demonstrated enhanced precision in peak ground acceleration prediction and seismic zone classification. Despite their advantages, metaheuristic techniques face several open challenges. These include scalability to large-scale problems, lack of standard benchmarks and datasets, computational expense in high-fidelity simulations, and limited transparency in multi-stage or learning-augmented models. Moreover, reproducibility and generalizability of results remain underdeveloped due to inconsistent reporting standards and proprietary data. This review highlights the need for community-driven initiatives to establish open datasets, reproducible benchmarking platforms, and standardized performance metrics. Future directions emphasize lightweight, adaptive algorithms capable of operating in real-time environments, as well as interpretable and sustainable optimization frameworks suit-able for deployment on embedded systems and edge devices. In summary, metaheuristic optimization holds immense promise for advancing earthquake resilience. Its continued development—through hybridization, integration with AI, and emphasis on transparency and real-world applicability—will be instrumental in shaping the next generation of intelligent seismic risk mitigation tools.

Keywords: Earthquake engineering; Genetic Algorithms; Article Swarm Optimization; Differential Evolution; Ant Colony Optimization; Grey Wolf Optimization

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1 Introduction

Earthquakes are one of the most hazardous natural occurrences that are most debilitating to human lives, instigation, as well as financial security in various parts of the world. [1] Effective mitigation of seismic risks necessitates resolution of various, multi-dimensioned optimization problems encountered in structural engineering, earthquake retrofitting, geophysical inversion and emergency resource management. The issues tend to be nonlinear, non-convex and subject to high epistemic and aleatory uncertainty, making conventional optimization methods inappropriate in practice, like it is the case with linear programming or gradient descent, or exhaustive search. Recent advancements in earthquake engineering have demonstrated the vital role of metaheuristic optimization techniques in addressing complex, nonlinear, and uncertain seismic design challenges. this abstract contrasts the traditional deterministic optimization methods, such as linear programming and static structural models, with adaptive and data-driven approaches powered by modern metaheuristics. The crumbling infrastructure on the left symbolizes the limitations of classical methods under uncertainty, while the robust, base-isolated buildings on the right illustrate the success of algorithms like Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Grey Wolf Optimization (GWO), especially when applied in hybrid forms like PSO-GWO and GA-PSO. Incorporated within the figure are symbolic representations—flocks of birds for swarm intelligence, DNA strands for evolutionary computation, and Pareto fronts and feedback loops for multi-objective and real-time optimization strategies. Additionally, the presence of neural network motifs, sensor networks, and data curves illustrates the integration of metaheuristics with machine learning and real-time decision support systems. This interplay is essential for enhancing earthquake resilience through intelligent infrastructure planning, control, and monitoring.

In recent years, metaheuristic optimization algorithms have emerged as powerful alternatives to classical methods, offering robust and flexible approaches for solving large-scale, real-world optimization problems where mathematical models may be noisy, discontinuous, or analytically intractable [2–4]. Metaheuristics are nature-motivated procedures that are population-based search following algorithmic models that imitation bio-physical or social behaviors and supported the iterative advancement of candidate solutions.They have the advantage that they are insensitive to gradient information and can accommodate black-box representations, which makes them especially appealing to seismic engineering to which the uncertainties on material properties, ground motion behavior, and boundary conditions are generally present. The application of metaheuristics in earthquake-related studies began with early implementations of Genetic Algorithms (GA) for seismic source localization and expanded into other areas such as tuned mass damper design sensor placement optimization , and seismic isolator calibration . As the field matured, hybrid algorithms combining multiple paradigms—such as Particle Swarm Optimization (PSO) and Grey Wolf Optimization (GWO)—were developed to enhance search performance and convergence speed . Multi-objective variants like NSGA-II and MOPSO further allowed engineers to consider trade-offs between cost, structural weight, and performance in a Pareto-optimal framework. In the present day, the expansion of the availability of computational resources and the accessibility of large-scale seismic data has created a change of direction in all research toward data-based optimization solutions. These include surrogate-assisted metaheuristics, which use machine learning models to approximate costly finite-element simulations, and reinforcement learning–augmented frameworks that adaptively regulate structural responses in real time. For example, deep learning classifiers optimized via PSO and DE have shown significant improvements in the prediction of peak ground acceleration and seismic zone classification accuracy . These innovations are also increasingly applied in disaster management and energy dispatch in smart microgrids following seismic events . Albeit these developments, there still exists some major issues that are critical. Scalability of nonlinear soil structure interaction simulations is affected because they are computationally time-consuming as high-fidelity. Many published studies lack standardized datasets and performance benchmarks, impeding reproducibility and cross-comparison [5–7]. Moreover, black-box character of most metaheuristics makes the interpretation difficult and decreases their adoption in code-based structural design, where regulation requires transparency of decision-making process. The purpose of the review is to make an attempt by systematically reviewing the literature and synthesizing it to obtain a clear idea of the research work that has been done in the field of metaheuristic optimization as applied to earthquake engineering. We give a time- and topic-based discussion of the progress of algorithms, separated into the fundamental single-algorithm methods, hybrid metaheuristic methods, multi-objective methods and more contemporary combinations with machine learning. There is particular focus on the use areas of structural control, seismic inversion, early-warning classification and emergency resources planning. The objectives of this review are threefold: (1) to summarize the evolution and taxonomy of metaheuristic algorithms applied in seismic contexts; (2) to evaluate their performance, strengths, and limitations across different use cases; and (3) to identify future directions for research, including the integration of explainable AI, uncertainty-aware modeling, and digital twin technologies for resilient and adaptive infrastructure. This review will combine the knowledge of more than 50 scholarly sources in a bid to provide engineers, researchers, and policymakers who are in the business of planning and optimizing seismic resilience, with a reference point. It not only stresses the technical potential of metaheuristics but also the importance of transparency, standardization and real-life applicability in a serious decision-making area like seismic management.

Dangers of Earthquakes

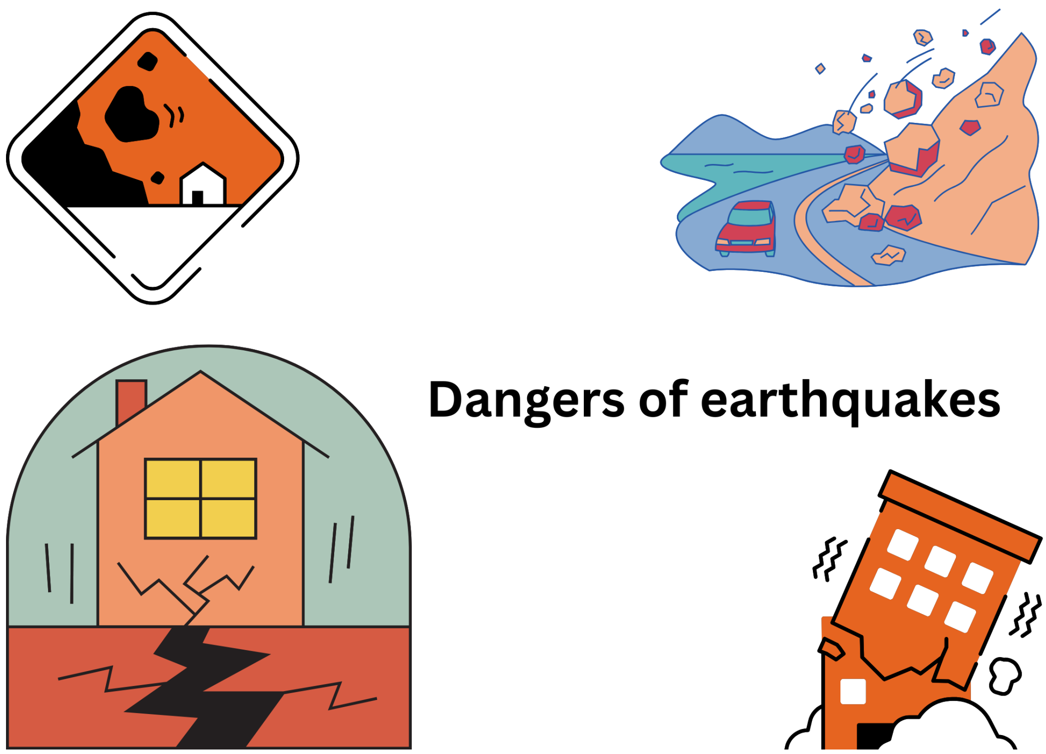

Figure 1: Illustration of the dangers of earthquakes

Earthquakes present one of the ugliest forms of natural calamities that are more capable of destroying lives, infrastructure, and habitat. The main hazard that occurs when an earthquake takes place is shaking of the ground that makes buildings, bridges and roads collapse. Particularly weak are poorly constructed or designed structures. When it occurs in crowded places, it poses a great risk of death and injuries caused by falling objects as well as collapsing roofs or building downfall. People can also be entrapped under a pile of debris leaving people with serious physical and psychological shock. The other significant threat that earthquakes possess is called surface rupture. It happens in situations where the earth is torn apart along a fault line ripping roads, pipelines, and buildings. Such breaks may leave key infrastructure disabled, leaving people unable to access emergency services, water, and electricity. Damage to the lined gas could result in fires or explosions which further enhances the disaster and makes rescue more challenging. Earthquakes in the sea lead to the occurrence of tsunamis in coastal areas; huge waves which move with high velocity and cover shores within minutes. These tsunamis have a potential to cause massive floods, drownings and other damage to structures. And even inland, the tremors have the effect of causing landslides in mountainous regions, suffocating dwellings and roads under the weight of tons of soil and rubble.

1.1 Challenges in Seismic Optimization

Seismic optimization tends to uniquely define the concerns because the phenomena associated with earthquakes are unpredictable and dynamic. In contrast with standard engineering optimization problems, where the loads are usually assumed to be static and known, and the constraints are well-characterized, seismic

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optimization involves solution of time-varying loads of uncertain quality, consideration of nonlinear system responses, and multi-objective trade-offs in situations of uncertainty. The complexities render the classical deterministic optimization methods to be not so efficient and emphasize the importance of strong, flexible metaheuristic algorithms. However, there are still a number of technical, computational, and practical constraints that prevent successful implementation of metaheuristics approach in this area. The first problem is that the seismic engineering design space is highly nonlinear and high dimensional in nature. Dynamic building system interaction series between the ground motions, the structural materials, damping devices, and the boundary conditions are the structural response due to earthquakes. It may tend to make objective functions discontinuous, having no derivatives (non-differentiable), and having lots of local minimas. Such conditions are well suited to metaheuristic algorithms, which however can still have convergence problems, especially in very large or multi-modal search space in which premature convergence or the time exceeding the computation can take place. Also, there are no standard benchmarks, reproducibility practices, hindering the field of research. In contrast to other fields of research e.g. machine learning or structural optimization under static loads, the seismic optimization community does not enjoy a general set of benchmark tasks, data and evaluation measures. The lack renders it hard to compare the outcomes among studies, and makes the generalization of discoveries to new constructions types or seismic areas. The system further hampers replication and knowledge transfer due to inconsistent reporting of parameters of the algorithm, boundary condition and computational settings [8]. On the practical side, many metaheuristic algorithms are treated as black boxes that pose some issues in regards to transparency and regulatory approval. Several engineering works, and especially those concerned with the structural and civil fields, are performed under high safety codes and design standards. The regulating institutions and decision-makers will hesitate to believe solutions made by the algorithm that has no explanation of why they do so. Efforts are currently underway to integrate explainable artificial intelligence (XAI) into optimization frameworks, aiming to make search trajectories, sensitivity analyses, and constraint handling more interpretable to engineers and reviewers. Lastly, the applicability of real time is throttled. Earthquake early warning applications, adaptive structural control and emergency resource dispatch applications have to have optimizations running within seconds. The capacity of most metaheuristic algorithms (and typically in the high-dimensional case) to work within these time limits is not yet determined. Light weighted clauses of classical algorithms as well as parallel processor approaches are under investigation, and general real time usage remains an ideal in the future. [9] To sum it up, although metaheuristics have strong potential to solve seismic optimization problems, their application is limited by a number of domain specific issues: the nonlinear and stochastic design spaces, computational overhead, absence of benchmarked approaches, shortcomings in terms of transparency of problem formulation and solutions, as well as the inability to run in real-time. These barriers will need not merely algorithmic advance but additionally transdisciplinarity among seismologists, engineers, and computer scientists.

1.2 Background on Metaheuristic Algorithms

Metaheuristic algorithms refer to a broad class of optimization algorithms, which are effective to address very severe, non-linear and multi-dimensional issues, where classical optimization methods cannot be not sufficiently effective. Such algorithms do not use gradient information and make no very strong assumptions about continuity or convexity. Instead, they explore huge and usually poorly understood solution landscapes to attain near-optimal answers through stochastic and heuristic methods. The term "metaheuristic" combines the Greek words "meta" (meaning beyond or higher-level) and "heuristic" (referring to problem-solving strategies that guide discovery). Generally in the simplest terms a metaheuristic is a high level framework that determines the behaviour of a set of low level heuristics in order to find an optimal solution. Unlike exact algorithms that guarantee convergence to the global optimum (often at a prohibitive computational cost), metaheuristics prioritize flexibility, speed, and scalability, making them particularly suitable for real-world engineering problems—especially in fields like earthquake engineering, where the solution space is often highly discontinuous and impacted by dynamic external inputs. Similarly to relative large extent, metaheuristics can be classified into few families depending on their degree of inspiration; whether biological, physical or social. Evolutionary Algorithms (EAs), including Genetic Algorithms (GA) and Differential Evolution (DE), are among the earliest and most widely applied types. These algorithms resemble to the natural selection in which they employ mutation process, crossover and selecting processes. GA has managed to be quite successful in civil, seismic engineering to optimize structural layouts, to tune mass dampers and to retrofit buildings since it does not experience local minima. Swarm Intelligence (SI) methods form another important class. Inspired by the collective behavior of biological organisms such as bird flocks, ant colonies, or fish schools, these algorithms include

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Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), and Artificial Bee Colony (ABC). PSO can be given as an example, in which behavior of moving particles in the multi-dimensional search space is modeled in a way that in order to make a correction to its position, each particle can do so based on the experience that it and its neighboring particles have. The methods are effective on continuous optimization problems, and have already been successfully applied to optimise the parameters of seismic isolators, sensor networks and control systems of base-isolated structures. A third category comprises physics-inspired algorithms, such as Simulated Annealing (SA), Gravitational Search Algorithm (GSA), and Harmony Search (HS). These are based on the laws of thermodynamics, gravitation or the same with music improvisation, respectively. An example is Simulated Annealing, where one simulates the action of annealing of metals, to allow that solutions sometimes worsen so that they can escape the local optima. Relatively easier implementations and tuning are the major strengths, in general, of such approaches to be used in preliminary design optimization in seismic applications. Most recently a variety of socio-political and human based metaheuristics have been created. These include Teaching–Learning-Based Optimization (TLBO), Imperialist Competitive Algorithm (ICA), and League Championship Algorithm (LCA). These algorithms play up learning behavior, political contest or sports leagues to inform solution development. Being comparatively new such algorithms provide exciting properties such as low parameter sensitivity and enhanced trade-offs between exploration and exploitation. To this compendium of classical and novel metaheuristics one can add a trend towards hybridization, that is, to use two or more algorithms in concert in order to exploit their synergetic advantages. e.g. a PSO GWO hybrid may combine the global convergence capabilities of PSO with the local refinement power of GWO. These hybrid algorithms are particularly useful in seismic design problems where both global performance (e.g., energy dissipation) and local constraints (e.g., inter-story drift) must be simultaneously optimized. The techniques of metaheuristics have also been in a position to combine itself with the machine learning algorithm and surrogate model so that it could compute low costs in the process. When implementing complex finite-elements to repeatably implement the system behavior becomes costly, the surrogate models (Kriging, radial basis functions or even neural networks) are trained to simulate the system behavior. These surrogates are then optimized using the meta-heuristics and the design cycle is significantly accelerated. [10] In short, meta-heuristic algorithms form a multi-faceted and dominant rule within the optimization in the scope of complex, uncertain, and multi-goal problem areas of issues. They are quite fit to use in the engineering practice that deals with earthquakes, because they can perform in higher dimension, they can be taught to do non-convex behavior and they can be taught by a noisy evaluated signal. The work of metaheuristics is projected to increase even more as the seismic design and seismic related control systems become ever more data centric and adaptive, especially with the presence of real time sensing, edge computing and intelligent control technologies.

1.3 Classification of Metaheuristics

The general criteria according to which the set of metaheuristic algorithms may be divided is rather limited and includes search strategies, sources of inspiration and population dynamics. These classifications should be studied in details to understand their strengths, limitations and locations which they can or can not be applied to.

1. According to Population Structure

Single-solution based metaheuristics These methods operate over a single candidate solution, that is progressively modified. Classic examples include Simulated Annealing (SA) and Tabu Search (TS). They are easier and have fewer memory requirements although they can have problems with local optima. item **Population-based metaheuristics**: These act on a population of solutions, permitting search of multiple areas of the search space concurrently. Algorithms such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) fall under this category. The population-based approaches are also relatively more immune to local optima and tend to be more appropriate to large-dimensional problems involving earthquakes.

2. According to Inspiration Source

- **Evolutionary Algorithms (EAs)**: Inspired by the natural process of evolution, these include Genetic Algorithms (GA), Differential Evolution (DE), and Evolution Strategies (ES). Their evolution moves through generations by using application of operation like mutation, crossover and selection.

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- **Swarm Intelligence Algorithms (SIAs)**: These draw inspiration from the collective behavior of biological swarms such as flocks of birds or schools of fish. Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO) are prime examples. They are quite useful with continuous optimization problems when used in seismic modeling.
- **Physics-based Algorithms**: These mimic physical laws and processes, such as the Simulated Annealing (SA), which emulates the annealing process of metals, or Gravitational Search Algorithm (GSA), which simulates mass attraction between objects.
- **Human-based and Socio-political Algorithms**: A more recent category where it is based on how humans make decisions or how one would teach–learn or act politically. Teaching-Learning-Based Optimization (TLBO) and Imperialist Competitive Algorithm (ICA) belong here. They can be used in volatile and unpredictable cases like the response to earthquakes in real time due to their flexibility.

3. Based on Objective Handling

- **Single-objective metaheuristics**: These focus on optimizing a single criterion. While simpler, they may not reflect the trade-offs often present in seismic design (e.g., cost vs. performance).
- **Multi-objective metaheuristics**: These algorithms optimize multiple conflicting objectives simultaneously and aim to generate a Pareto front of non-dominated solutions. Examples include Non-dominated Sorting Genetic Algorithm II (NSGA-II) and Multi-Objective Particle Swarm Optimization (MOPSO). These are widely used in structural engineering applications where multiple design goals must be balanced.

4. Based on Learning and Adaptation

- **Static metaheuristics**: These use fixed parameters and search strategies throughout the optimization run. While simpler to implement, they may not adapt well to changes in the problem landscape.
- **Adaptive and Self-adaptive metaheuristics**: These modify their parameters or strategies dynamically based on feedback from the search process. Examples include adaptive DE, and Reinforcement Learning–integrated metaheuristics. These are especially valuable in real-time earthquake warning and adaptive structural control.

This classification framework aids in selecting the most appropriate metaheuristic algorithm for specific earthquake engineering tasks—whether it's sensor placement, structural optimization, or seismic inversion—based on the complexity, dimensionality, and multi-objective nature of the problem.

2 Related Work

Over the past three decades, the integration of metaheuristic algorithms into earthquake engineering has undergone substantial evolution. Early studies recognized the inadequacy of classical optimization techniques—such as linear programming and gradient-based solvers—in addressing the highly nonlinear, uncertain, and multi-modal nature of seismic design and analysis problems. This gap motivated the adoption of nature-inspired metaheuristics capable of globally exploring complex search spaces under real-world constraints. The earliest applications of metaheuristics in seismology date back to the 1990s, with Genetic Algorithms (GA) emerging as a promising tool for inverse problem-solving and seismic source localization. One of the pioneering contributions in this domain was presented by [11], who demonstrated that GA could robustly estimate earthquake epicenters using noisy arrival-time data. This study laid the foundation for a broader acceptance of evolutionary computing in geophysical contexts, showing that biologically inspired global search methods could outperform deterministic routines in non-convex search landscapes. Throughout the early 2000s, other metaheuristic paradigms gained traction, particularly Particle Swarm Optimization (PSO) and Differential Evolution (DE). In some structural applications, these algorithms were more convergent and less

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sensitive to parameters as compared to GAs. For example, [12] applied DE to optimize the dynamic properties of seismic isolators, achieving substantial reductions in structural drift under simulated earthquake scenarios. Around the same time, other researchers [13] began to explore the theoretical underpinnings and limitations of standalone metaheuristics in structural dynamics, contributing to the refinement of constraint-handling strategies and fitness function tuning. The period of hybrid and multi-stage frameworks became the next stage in the discipline between 2010 and 2015. Such strategies evolved due to continuation issues like premature convergence as well as unreasonable computation cost. [14] employed Ant Colony Optimization (ACO) to fine-tune the mass and damping configuration of tuned mass dampers (TMDs) in high-rise buildings, improving vibration control under strong ground motions. Concurrently, [15] introduced a hybrid PSO–Grey Wolf Optimization (GWO) algorithm for seismic design of arch dams, capitalizing on the exploration–exploitation balance offered by multi-algorithm integration. These studies revealed that hybrid metaheuristics not only enhanced convergence reliability but also provided more diverse solutions in complex design spaces. Another notable advancement was the integration of finite element feedback within the optimization loop. [16] proposed a real-time soil–structure interaction model embedded within a metaheuristic framework. Their approach marked a step forward in simulation–optimization coupling, allowing seismic performance evaluation to be updated adaptively based on ground motion variability and foundation conditions. From 2015 onward, the literature shifted toward multi-objective optimization frameworks. Algorithms such as NSGA-II and MOPSO became widely adopted to simultaneously optimize conflicting objectives like structural cost, mass, and performance indices. For example, [17] applied MOPSO to optimize base-isolated structural systems, while [18] demonstrated the use of NSGA-II for budget-constrained seismic retrofitting of masonry buildings. These studies introduced the concept of Pareto efficiency to the domain, allowing engineers to select from a suite of equally optimal solutions based on project-specific constraints. The most recent wave of research has seen the integration of machine learning and artificial intelligence into metaheuristic pipelines. [19] introduced a GA–PSO hybrid for optimizing seismic sensor placement in early warning systems, improving fault coverage and alarm accuracy. . [20] and [21] used PSO and DE, respectively, to tune neural classifiers for peak ground acceleration prediction and seismic zone classification. These machine-learning–augmented metaheuristics showed considerable gains in accuracy and generalization over traditional rule-based models. Cutting-dge research from 2023 onward has expanded into reinforcement learning (RL)–integrated optimization. [22] introduced a PSO-guided reinforcement learning controller for adaptive base-isolated structural systems. Their model adapts control strategies in real time based on seismic feedback, showcasing the potential of closed-loop intelligent control in earthquake engineering. Similarly, [23] applied deep learning with metaheuristic-based hyperparameter tuning to optimize post-earthquake resource allocation, specifically in microgrid energy management under constrained conditions. Despite the growing body of work, reproducibility and standardization remain critical bottlenecks. As noted in surveys , many metaheuristic studies suffer from incomplete reporting, proprietary datasets, and absence of open-source code—challenges that hinder longitudinal analysis and real-world deployment. Moreover, the lack of unified benchmarks makes it difficult to compare the performance of algorithms across different seismic applications. Recent community-driven efforts are beginning to address these gaps. Repositories like SSRN and various open-access initiatives are working to compile standardized datasets and metaheuristic configurations, with the goal of establishing reproducible workflows and benchmark suites. However, these efforts require broader adoption and interdisciplinary collaboration across seismology, structural engineering, and computational intelligence communities. In summary, the literature reveals a clear trajectory of innovation—from early single-algorithm studies to hybrid, multi-objective, and AI-enhanced frameworks. Metaheuristics have proven invaluable for solving complex optimization problems in earthquake engineering, but continued progress will depend on improving transparency, establishing benchmarks, and integrating domain-specific knowledge into algorithm design.

3 Methodology

This literature review follows a structured and systematic approach to collect, filter, and analyze research studies involving metaheuristic optimization in earthquake-related engineering applications. The goal is to identify algorithmic trends, categorize applications, and evaluate methodological quality across diverse problem domains. To begin, relevant publications were retrieved using targeted keyword combinations such as "metaheuristic," "seismic optimization," "earthquake engineering," "structural control," "sensor placement," "multi-objective optimization," and "machine learning." These keywords were applied to academic databases including Scopus, IEEE Xplore, ScienceDirect, SpringerLink, and Google Scholar. The search spanned from 1992 to 2025 to encompass both foundational work and contemporary developments. Studies were included if

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they applied, modified, or evaluated metaheuristic algorithms in the context of seismic or earthquake-related problems. Eligible applications included structural design optimization, base-isolated system tuning, seismic inversion, early-warning system enhancement, ground motion classification, and disaster resource allocation. Publications without experimental validation, reproducibility details, or relevant problem domains were excluded. Each selected study was classified according to the type of metaheuristic algorithm used (e.g., Genetic Algorithm, Particle Swarm Optimization, Differential Evolution, Ant Colony Optimization, hybrid approaches), the nature of the optimization task (e.g., single-objective vs. multi-objective), and the level of integration with simulation models or learning frameworks. Further categorization was performed based on the engineering objective, such as minimizing inter-story drift, optimizing material cost, improving energy dissipation, or maximizing sensor network coverage A qualitative comparison was then conducted across the reviewed studies using criteria such as convergence speed, robustness to uncertainty, computational efficiency, scalability, and real-world applicability. Although differing problem setups and performance metrics limited quantitative cross-study comparison, relative improvements reported in each study were carefully analyzed within their experimental context. Finally, observed research gaps, recurring challenges, and opportunities for future work were synthesized based on methodological patterns across the literature. This methodological framework enables a comprehensive understanding of how metaheuristic optimization is shaping the future of earthquake-resilient engineering.

3.1 Classification Framework

The selected studies were then classified based on:

1. **Type of Metaheuristic:** Evolutionary (e.g., GA, DE), Swarm-based (e.g., PSO, ACO), Physics-inspired (e.g., SA), and Hybrid approaches.
2. **Application Domain:** Structural optimization, vibration control, ground motion modeling, early warning systems, sensor placement, and disaster resource allocation.
3. **Optimization Objective:** Single-objective vs. multi-objective; deterministic vs. uncertainty-aware.
4. **Integration Level:** Classical vs. machine learning–assisted vs. real-time reinforcement learning–enhanced.

This classification allowed for meaningful comparisons across problem domains and algorithm types, highlighting trends and performance trade-offs over time.

3.2 Comparative Evaluation

Each algorithm and study was assessed based on multiple qualitative and quantitative performance indicators:

- **Convergence speed:** Time required to reach stable solutions.
- **Solution quality:** Proximity to known optima or improvements over baseline methods.
- **Robustness:** Ability to maintain performance under noisy or uncertain data.
- **Computational efficiency:** Resource consumption relative to problem size and fidelity.
- **Real-world applicability:** Use in simulations, testbeds, or field deployments.

Where numerical results were not directly comparable due to differing benchmarks, studies were evaluated in terms of relative improvement within their own experimental context.

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3.3 Limitations

While every effort was made to ensure objectivity and comprehensiveness, this review is subject to limitations. First, publication bias may exist as studies reporting successful metaheuristic results are more likely to be published. Second, lack of standard datasets and metrics across studies limits direct performance comparison. Third, some newer techniques (e.g., reinforcement learning integration) are still in early stages of validation. Nonetheless, the adopted methodology provides a rigorous framework for synthesizing insights across diverse applications and identifying promising directions for future research in seismic metaheuristic optimization.

Table 1: Representative metaheuristic and AI-based optimization studies in earthquake engineering and related domains.

Ref.	Algorithm	Application	Contribution
[1]	DE, HFA, NRO, LSA, HHO, TSA + RF	Energy absorption prediction in aseismic concrete	TSA–RF hybrid performed best; sensitivity analysis identified cement as critical; validated AI for tunnel engineering materials.
[2]	PSO	Metaheuristic survey	Comprehensive review of PSO variants.
[3]	Hybrid Metaheuristics	Base-isolation system design	Optimized hybrid configurations for improved seismic isolation.
[4]	MDVC-UIBB-BC	Performance-based seismic design	BB-BC/HS hybrid with cascade DVC; reduced computation; effective pushover optimization.
[11]	GA	Epicenter localization	Early demonstration of GA for seismic inversion.
[14]	ACO	Tuned-mass damper optimization	Reduced structural vibration under seismic loading.
[19]	GA–PSO	Sensor placement	Improved fault coverage and alarm accuracy.
[12]	DE	Seismic isolator tuning	Improved identification of isolator properties.
[15]	PSO–GWO	Arch dam optimization	Enhanced convergence for dam geometry optimization.
[17]	MOPSO	Base-isolated structures	Produced Pareto-optimal trade-offs for cost, weight, and drift reduction.
[18]	NSGA-II	Masonry retrofitting	Generated effective retrofit strategies under budget constraints.
[22]	PSO + RL	Structural control	Real-time adaptive control for base-isolated buildings.
[20]	PSO–NN	PGA prediction	Achieved up to 30% improvement in PGA estimation.
[21]	PSO–DE	Seismic zone classification	Enhanced classifier generalization across datasets.
[24]	HSMPSO–SCA	Optimal power dispatch	Hybrid method for improved power flow optimization.
[23]	Metaheuristics + RL	Emergency logistics	Optimized post-earthquake resource allocation strategies.
[5]	Surrogate ML models	Seismic optimization	Reduced computation time using ML-based surrogates.
[6]	Repository	Literature aggregation	Comprehensive metaheuristic review resource.
[13]	Evolutionary Algorithms	Structural seismic design	Survey of multi-objective evolutionary design techniques.
[16]	Metaheuristics + FE	Soil–structure interaction	Coupled FE–metaheuristic loop for SSI optimization.
[25]	Hybrid metaheuristic	Structural optimization	Introduced a novel hybrid optimization framework.
[26]	—	Concrete strength optimization	Sustainable modeling of compressive strength.
[27]	TSA–WOA	Solar forecasting	Enhanced ensemble forecasting performance.
[28]	Coati Optimization	Energy forecasting	Introduced Coati–SVR hybrid for improved prediction.
[29]	Metaheuristics + FEM	SSI optimization	Real-time FE-based soil–structure interaction design.
[30]	Adaptive DE	Sensor placement	Dynamic DE adaptation for improved sensor deployment.
[31]	Improved AOA	Near-fault optimization	Captured nonlinear behavior under pulse-type motion.
[32]	Metaheuristic–ML	Shear wall capacity	Metaheuristic-tuned ML models outperformed empirical formulas.
[33]	Bayesian Optimization	Damage-grade prediction	Identified top-performing ML models for earthquake damage grading.
[34]	Metaheuristics	Mining seismic hazard	Improved prediction of mining-induced seismic bumps.
[35]	ANN	RC frame design	Demonstrated ANN feasibility for earthquake-resistant RC design.

This literature review follows a structured methodology to ensure comprehensive coverage and critical synthesis of metaheuristic optimization techniques applied to earthquake-related problems. The goal was to capture

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the historical progression, diversity of algorithmic approaches, and breadth of application domains.

4 Discussion

The application of metaheuristic algorithms in earthquake-related optimization problems has significantly evolved over the past three decades. This review highlights the growing versatility, robustness, and adaptability of these algorithms in addressing the unique challenges of seismic modeling, structural control, sensor deployment, and emergency planning. Traditional deterministic optimization techniques often struggle with the nonlinearity, high dimensionality, and uncertainty inherent in earthquake engineering problems. Metaheuristics, by contrast, offer flexible frameworks capable of exploring complex solution spaces, tolerating noisy or incomplete data, and managing multi-objective trade-offs. A key trend observed across the literature is the increasing adoption of hybrid metaheuristics, which combine the strengths of multiple algorithms. For instance, PSO–GWO hybrids leverage fast convergence from PSO and strong local search from GWO, making them particularly effective in structural design optimization. Similarly, GA–PSO combinations have shown promise in sensor network layout and fault detection tasks. These hybrid strategies often outperform single-algorithm approaches, albeit at the cost of increased computational complexity and parameter tuning requirements. Another important development is the integration of metaheuristics with machine learning and reinforcement learning. Such combinations allow for adaptive optimization in real-time scenarios, such as earthquake early warning systems or base-isolated building control. PSO-tuned neural networks and metaheuristic-enhanced classifiers have demonstrated notable accuracy improvements in predicting peak ground acceleration and classifying seismic zones. Despite these advancements, several challenges persist. Reproducibility is limited by the lack of standardized datasets and benchmarking protocols. Many studies also fail to report critical hyperparameters, hindering comparative analysis. Moreover, real-time deployment remains difficult for many computationally intensive metaheuristics, especially when embedded systems or low-power hardware are involved. Future research should prioritize the development of lightweight, interpretable, and adaptive metaheuristic frameworks that balance accuracy with computational efficiency. Open-source libraries, shared benchmarks, and cross-domain collaborations will be essential in bridging the gap between theoretical advances and practical, field-deployable earthquake mitigation systems. A clear trend in the literature is the evolution from single-algorithm frameworks to hybrid metaheuristics. Early applications of GA, PSO, and DE demonstrated sufficient performance for basic problems such as seismic inversion or parametric tuning. However, the inherent limitations of each algorithm—such as premature convergence in PSO or slow convergence in GA—spurred the development of hybrid methods that combine the strengths of different search paradigms. For instance, PSO–GWO hybrids leverage PSO's fast exploration with GWO's exploitation capacity, yielding better performance in complex structural design tasks [15]. Similarly, GA–PSO ensembles allow robust parameter estimation in sensor optimization [19]. These hybrid methods tend to outperform their standalone counterparts in convergence speed, solution accuracy, and robustness. However, the added complexity can result in increased computational cost, reduced transparency, and difficulties in reproducibility. Metaheuristics have found application across a diverse range of earthquake-related problems, spanning both pre-disaster and post-disaster domains. In structural engineering, they are used to optimize seismic isolator parameters, tuned mass damper configurations, and cross-sectional geometry of infrastructure. In geophysical applications, they aid in seismic source localization and nonlinear inversion. Meanwhile, in early-warning and post-event response, metaheuristics enable optimized sensor placements, improved classification accuracy for seismic events, and efficient allocation of emergency resources. This breadth underscores the versatility of metaheuristics as general-purpose optimizers. However, domain-specific adaptations are often required. For instance, structural optimization may involve physical constraints such as load-bearing capacity or material fatigue, while early-warning systems prioritize real-time performance and false positive minimization. The ability to embed domain knowledge into fitness functions and constraint-handling mechanisms is crucial for performance and real-world relevance.

4.1 Rise of Multi-Objective and Real-Time Systems

Another major theme is the growing prominence of multi-objective optimization. Problems such as structural retrofitting or dam design often involve trade-offs between cost, safety, and performance. Metaheuristics such as NSGA-II and MOPSO have become standard tools for generating Pareto-optimal solutions in these contexts [17, 18]. Multi-objective metaheuristics not only improve decision-making but also provide engineers

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with flexibility by offering multiple optimal solutions instead of a single deterministic one. Parallel to this, there has been a push toward real-time optimization systems. Lightweight variants of Firefly and Whale Optimization algorithms have been designed to operate on embedded platforms with strict latency constraints [27]. These are particularly relevant for applications such as early-warning systems, where decision timeframes are measured in seconds or less. Yet, benchmarking real-time performance across different hardware and platforms remains underexplored. The integration of metaheuristics with machine learning and reinforcement learning represents a significant leap forward. Metaheuristics have been used to tune hyperparameters of classifiers for seismic magnitude prediction [20,21], optimize the structure of neural networks, and guide learning in deep reinforcement learning agents for microgrid management and structural control [22,24]. These hybrid pipelines improve accuracy, generalization, and adaptability—especially in dynamic or uncertain environments. However, they come with challenges. Learning-based systems often require large datasets for training, which are scarce in the seismic domain. Moreover, the black-box nature of deep models, combined with the stochastic nature of metaheuristics, raises concerns about interpretability and trustworthiness in high-stakes settings. Despite promising advancements, the field suffers from a lack of standardized benchmarks. Few studies use the same datasets, metrics, or test environments, making fair comparisons difficult. Performance is often reported in isolation, with no clear baselines or statistical robustness (e.g., confidence intervals, significance tests). This hinders meta-analysis and the ability to track algorithmic improvements over time. Moreover, many implementations remain closed-source or inadequately documented. Hyperparameter settings, termination conditions, and problem formulations are often underreported, impeding reproducibility. These limitations call for the development of open-source metaheuristic libraries, curated ground-motion datasets, and shared benchmarking platforms tailored to seismic applications. Metaheuristics are inherently computationally intensive, especially in problems involving high-dimensional search spaces or real-time requirements. Structural optimization involving finite-element simulations or dynamic soil–structure interaction models can take hours or days to evaluate a single fitness function. As a result, many studies are limited to small-scale or simplified models. Some progress has been made through parallelization and surrogate modeling. For example, machine-learning-based surrogate models can approximate computationally expensive simulations, allowing metaheuristics to evaluate solutions more quickly. However, these approaches require careful training and validation to avoid introducing approximation errors.

Several overarching trends and challenges have emerged:

- **Hybridization vs. Complexity**: Hybrid metaheuristics outperform standalone methods [17, 18] but at the cost of increased algorithmic complexity and reduced transparency [16].
- **Multi-objective Trade-offs**: Real-world seismic design requires balancing safety, cost, and computational efficiency. NSGA-II and MOPSO facilitate Pareto-front exploration but often rely on static weighting schemes [17, 18].
- **Real-time Deployability**: Lightweight and adaptive variants meet stringent timing constraints in early-warning and control applications [20, 21], yet systematic hardware benchmarks are scarce.
- **Learning-Integrated Pipelines**: Metaheuristic-optimized machine-learning and reinforcement-learning systems enhance predictive accuracy and adaptivity [22, 23], but face data scarcity and interpretability issues.
- **Reproducibility and Benchmarking**: The field lacks common datasets, open-source code, and standardized metrics. Community efforts are needed to develop shared repositories and benchmark suites [16, 29].

Future directions include federated and distributed metaheuristics for decentralised sensor networks [30], metaheuristic neural architecture search for seismic classification [5], and explainable optimization frameworks for transparent decision support

4.2 Future Directions

The field is rapidly evolving, and several promising directions are emerging:

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- **Adaptive Metaheuristics:** Algorithms that dynamically adjust parameters based on convergence trends or environmental feedback (e.g., adaptive mutation rates, population sizes).
- **Federated Optimization:** Distributed metaheuristic frameworks that optimize across decentralized data (e.g., sensor networks in different regions), enhancing scalability and data privacy.
- **Metaheuristic Neural Architecture Search (NAS):** Using GAs or PSO to design the structure of neural networks for seismic classification or forecasting tasks.
- **Explainable Optimization:** Efforts to enhance transparency of metaheuristic decisions, especially when combined with opaque learning-based models.
- **Low-Power and Embedded Deployment:** Designing lightweight optimization frameworks for edge devices in early-warning systems or mobile response platforms.

To support these directions, a coordinated effort is needed across the community to develop open datasets, reproducible codebases, and standardized evaluation protocols.

5 Conclusion

Metaheuristic optimization techniques have now be important to the sphere of seismic risk minimizing. Their capability of effectively treating very complex, nonlinear, and multi-modal design spaces intends to determine why they are well-positioned to manage an inherent uncertainty and variability of earthquake-related engineering issues. The review has delivered a broad metaheuristic enforcement in earthquake engineering, comprising an extensive scope of undertakings inclusive of structural design optimization, seismic inversion, ground-motion categorizing, early warning system Development of the discipline shows that there are three prevailing lines of thought to show how the community tries to conquer the challenges of the world of engineering. First, the emergence of hybrid metaheuristic frameworks demonstrates the power of combining distinct algorithmic paradigms—such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Harmony Search (HS), and Differential Evolution (DE)—to simultaneously leverage global exploration and local exploitation. The hybrid solution strategies have always reached convergence more quickly and also of higher quality especially in high-dimensional design problems which include the case of base-isolated building control and arch dam geometry optimizations. Second, the development of multi-objective metaheuristic algorithms has provided engineers with the opportunity to be very articulate about considering trade-offs between incompatible goals. Optimization The optimization of important performance parameters, including material cost, structural weight, displacement limits, and energy dissipation can be done, simultaneously, using algorithms such as NSGA-II and MOPSO. Rather than providing a single "best" solution, these methods generate a Pareto front of equally optimal designs, offering engineers a spectrum of alternatives tailored to different operational priorities and constraints. Third, most recent work stresses on the combination of machine learning, surrogate modelling and reinforcement learning into the optimization loop. These data-guided improvements use cheap approximations of costly simulations, adjust search tactics to the problem dynamics and enable real-time decision-making. Metaheuristic-tuned neural networks and reinforcement learning controllers have particular potential to be autonomous structural response control engineers under dynamic seismic loading, especially as the response changes dynamically. In spite of these incredible developments, there are still issues that the field has to contend with. There is also the lack of standard benchmark datasets and single evaluation protocols that facilitate a comparison of results between different studies or generalizability of the findings to geographic areas and type of buildings. Moreover, the nonlinear soil-structure interactions can be modeled with finite element simulations with high-fidelity dynamics, still computationally demanding to use them in the context of real-time or large-scale optimization. Moreover, a significant proportion of metaheuristic methods are treated as black-box systems, and they do not provide much insight on their internal search dynamics, which cannot be used in engineering practice due to safety concerns, since they are regulated by codes and standards. In order to overcome these shortcomings, the following aspects must be the focus of future studies. First, the standardization of the benchmarking measures, open datasets, and the possibility to reproduce the experimental protocols should be developed and adopted as the open-source benchmarking suites in order to perform any meaningful cross-comparison and collaborative progress. Second, the interchangeability of metaheuristics with digital twin technologies and edge-computing frameworks will aid the presence of adaptive control in smart infrastructure to real-time responses to seismic events. Third, the incorporation of explainable artificial intelligence (XAI) into metaheuristic workflows can increase transparency and interpretability, allowing domain experts to better understand algorithmic decisions and validate results. Lastly, advancing uncertainty-aware metaheuristics—capable of modeling both epistemic (model-based) and aleatory (random) uncertainties—will improve the robustness and resilience of designs against unforeseen seismic disturbances. To summarize, metaheuristic optimization has come of age as a heuristic interest to a mature and adaptable framework to be used to progress earthquake resilience. Through the adoption of algorithmic hybridization, multi-objective reasoning, and data-driven adaptivity, as well as through the enhancement of reproducibility, transparency, and the arbitrariness of the calculation, the field is ripe to leave its dazzling theoretical trail and be deployed comprehensively. Future development of metaheuristic frameworks, emphasized by interdisciplinary cooperation and open research, will play an essential role in the development of smart resilient infrastructure systems that will be able to resist the increasing threats of the seismic hazards.

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