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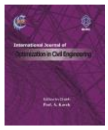

Advances in Optimization of Dams: A State of The Art Review

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ABSTRACT

Optimization strategies have turned out to be a requirement in the design and construction of dams because of the increasing demand for water resources, hydropower generation, and flood control and due to the inbuilt high cost and complexities of such massive structures (1) (2) (3) (4) (5) (6) (7). This review paper summarizes recent advances on dam optimization, covering a broad scope of dam types, primary objectives, approaches, and performance evaluation indices. It highlights the vast transition from traditional, at times time-consuming, trial-and-error based design techniques and classical optimization methods to efficient meta-heuristic (MH) and hybrid algorithms that outperform in terms of efficiency, accuracy, and global exploration (1) (3) (8). The paper also touches upon the growing application of Reliability-Based Design Optimization (RBDO) and robust optimization towards dealing with material property uncertainty, loading, and environmental uncertainties to achieve safer and cost-efficient designs (9) (10) (11). Ideal optimization objectives, such as volume reduction of concrete and dam safety maximization, are explored along with several geometric, stress, stability, and frequency constraints. Finally, it discusses the ongoing problems, including the computational expense and selection of appropriate algorithms, and instilling future research directions essential for further advancement of dam engineering practice.

Keywords: Meta-heuristic Algorithms; Reliability-Based Design Optimization (RBDO); Hydraulic Infrastructure.

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1. INTRODUCTION

Dams are significant infrastructure worldwide, serving different purposes like supplying water for drinking, agriculture, and industry, generating hydroelectricity, and also controlling

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devastative floods (4) (1) (2) (12) (13). Because of substantial safety and economic considerations, it is difficult to design & operate them properly (1) (2) (3) (4) (5) (6) (7). Conventional design methods rely on empirical rules, experience & iterative processes which may be time consuming, & may not produce the most optimal solutions from technical and economic standpoints (3) (8).

Because of these difficulties, optimization has become a crucial tool for solving linear and non-linear problems. This makes it easy to find solutions that yield the best results at the lowest possible cost and maximum profit (1). Over the past 20 years, research on water resources management has focused a lot of attention on dam reservoir operation (1). Traditional optimization techniques may not always be feasible due to their high time and cost requirements, as well as the complexity resulting from a range of goal functions and decision-making processes (1). Therefore, it is getting more and more important to use cutting-edge methods and contemporary technologies (1).

This review aims to provide an overview of the advances in dam optimization, drawing on different literary sources. It categorizes optimization by dam type, explains the evolution and application of different algorithms from classical to meta-heuristic and hybrid approaches, discusses common objective functions and constraints, and highlights critical performance evaluation criteria. It also explores the use of uncertainty parameters from the Reliability-Based Design Optimization (RBDO) method.

2. TYPES OF DAMS AND OPTIMIZATION FOCUS

Optimization studies include different types of dams, each possessing unique structural and operational challenges. The material and function of dams are important for developing the main focus of optimization.

2.1. Concrete Gravity Dams

These are among the most widely used structures in hydraulic engineering (14). The weight of dam is the main stabilizing force in these dams (14). Dams of such type can be optimized to reduce the cross-section area, minimizing the total volume of concrete and subsequent construction costs (15) (16) (17) (14). Overall stability against external forces is ensured along with controlling internal stresses (7) (14).

a) Cross-Section Shape: Genetic Algorithms (GA) and similar algorithms are employed in reducing the area of the trapezoidal cross-section (14). The studies show enormous savings, e.g., 11.9% volume saving with reference to the original designs or over 20% area saving of cross-section (7) (15).
b) Stability and Stress Analysis: The safety factor on float, toppling, and sliding can be computed using optimization algorithms (14). The stresses within the dam body and its foundation are checked and limited (17).
c) Dam-Reservoir-Foundation Interaction: Material nonlinearity and complex dam-reservoir-foundation interaction under dynamic loadings like earthquakes are considered in modern approach (16) (18).

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d) Drainage Gallery Position: Optimization may be utilized to determine the optimal position of drainage galleries to reduce uplift forces and increase dam stability, typically optimizing between 3m and 5m from the upstream face (10).
e) Optimization has been done on Theoretical dams (14), the Pine Flat dam in California (18), India's Tilari Dam (15), and India's Koonya concrete gravity dam, with a volume saving of 7.7% (17).

2.2. Concrete Arch Dams

Concrete arch dams are constructed to utilize the shape of the arch to transfer the water pressure to the valley sides so that the water pressure lifts and the arch only has to strengthen against the lift (13). Optimization of arch dams is focused on finding the optimum shape of dam to minimize concrete volume while preserving stability and strength (3) (6) (19) (20) (21) (22) (23) (12).

a) Shape characterization: Features such as radius of curvature, thickness along x and y-axes and central angle are prepared optimal (19) (6) (21). Typical optimization would involve considering approximately fifteen optimization factors.
b) Loading Type: It comprises static (self-weight, hydrostatic pressure) and dynamic loading types (earthquake excitations, hydrodynamic and temperature loading) (24) (16) (11) (18)].
c) Abutment Stability: The new designs consider abutment stability critical considering the bedrock geology and the forces from the dam (25).
d) Optimization of Stress Conditions: The new structure requires a significantly reduced amount of concrete usage, while at the same time keeping the levels of stress in the dam at safe limits, or even enhanced ones (19). For instance, the structural capacity of the dam reduced by 17.4%, while another alternative study indicated the reduction in tensile stress from 1.95 MPa to 1.16 MPa (19) (6).
e) Frequency Constraints: Impose limits on natural frequencies for improved dynamic performance and to prevent resonance during earthquakes (26).
f) Construction Stages and Real-World Problems: Real-world problems like multi-stage grouting, lift joint shear stresses, and minimum tensile stresses are dealt with (3).
g) The procedure has been successfully applied to actual dams like Iran's Karun IV arch dam (3), Morrow Point arch dam (26) (24), Xiamen arch dam (6), and Jiancaogou single-curvature arch dam in China (27). In China, approximately 30 arch dams have been optimized with an average of 20% reduction in their volume (28).

2.3. Earth Dams and Concrete Face Rock-Fill Dams (CFRD)

In the case of earth dams, optimization involves designing against a generalized function of one optimization criterion and factor analysis. In the case of Concrete Face Rock-Fill Dams (CFRD), optimization entails minimizing the cost of the dam while using material partition geometries and dam slope as design variables. The constraints are dam stability, stress, displacement, and stress level (5).

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a) Cost and Safety: Optimization studies aim to reduce quantities of the project in addition to engineering safety-related costs (5).
b) Geometric Variables: The design variables include the upstream and downstream slopes of the dam and the separate areas consisting of dam material (5).
c) Analysis for Stress and Deformation: Finite element calculations are performed to assess the deformational stress and stability of the slopes in the dam, thus meeting design specifications(5).
d) The Jishixia CFRD project is a relevant case study that demonstrates the efficiency of the optimization method in making it possible to construct dams with steeper slopes and wider downstream sections of rock-fill at lower costs, while ensuring stability and deformation within acceptable levels (5).

2.4. Dam Reservoirs (Operation Optimization)

For ensuring effective distribution of water resources and resolving the various, often contradictory demands of industries, agriculture, drinking water supply, power generation, and environmental protection, the optimal use of dam reservoirs has to be achieved (1).

a) Maximizing the Benefits: This involves reducing the occurrence of downstream flooding, ensuring a stable source of water, and optimizing the generation of hydroelectricity (1) (2).
b) Deficit Reduction: It entails addressing water supply infrastructure shortages (1).
c) During drought or water-scarce conditions, water from reservoirs can be utilized effectively through the adoption of hedging policies (1).
d) System Types: The studies examine single-objective and multi-objective reservoirs, and single and multi-reservoir systems (1).
e) The ever-increasing advancements in meta-heuristic strategies help significantly in overcoming the challenges related to real-time reservoir management.
f) The Karun 4 reservoir system, the Voshmgir, and the Golestan dams are examples of advanced algorithms that maximize the operational efficiency of reservoirs. A study of 76 academic articles geared towards the improvement of dam reservoir operation between 2002 and 2021 identified that Hybrid algorithms covered 18.68% of the methodologies used, while Genetic Algorithms covered 16.48% and appeared to be the most dominant strategies showing enhanced performance over classical or stand-alone meta-heuristic approaches (1).

3. METHODS AND STRATEGIES FOR OPTIMIZATION

Dam optimization was one of the areas whose development was quite phenomenal in the recent years, more particularly the growth in the preference for a move from classic mathematical programming approaches to the newer meta-heuristic and hybrid ones. The trigger for the development is primarily the increasing difficulty and the multi-dimensionality of real-life applications (1).

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3.1. Transition from Traditional Methods to Meta-heuristic Methods

Classic optimality procedures, for example, Linear Programming (LP), Dynamic Programming (DP), Stochastic Dynamic Programming (SDP), and Nonlinear Programming (NLP), often grow more complicated and expand temporal concerns upon themselves, especially in the high-dimensional nonlinear scenarios like the ones faced in multi-water dam systems and wide electricity production plants (1). Furthermore, such methodologies are defined by slow rates of convergence and a tendency to get trapped in local optima (1) (5).

Contrarily, the MH algorithms have been given due credit for the effectiveness in achieving near-global optimum solutions, a fact supported by high convergence rates of the algorithms (1). The methodologies are gradient-free and usually more convenient to employ compared to the traditional procedures (1). The past years have seen notable advancements in the application of MH strategies in a great part of the sectors in water resources management and dam design (1).

3.2. Common Meta-heuristic Algorithms

<u>Genetic Algorithm (GA):</u>

- The algorithm has been among the most powerful and successful evolutionary techniques found. It has been widely used for dam cross-sections, shape, and reservoir operation strategy optimization (1) (14) (7) (17) (15) (27).
- To overcome the limitations due to suboptimal performance, premature convergence, and declining search effectiveness, adaptive genetic algorithms and parallel genetic algorithms have been introduced. (5).
- Often considered to be the standard for today's meta-heuristic procedures (1).

<u>Particle Swarm Optimization (PSO):</u>

- Highly effective for various dam optimization problems, including dam structure and reservoir operation (22) (16) (24) (1) (29) (17) (4) (26).
- Known to be highly effective in solving convergence problems concerning local optima while achieving high accuracy very fast (4).
- Additional advancements, including IPSO, came along to make the search for world-wide solutions easier (22).

<u>Bat Algorithm (BA):</u>

- The effectiveness of reservoir management was assessed through the minimization of water supply deficits, achieving desirable results through the use of hedging measures (1).
- The enhanced bat algorithm (IBA) and the bat-swarm algorithm hybrid (HB-SA) enhance the ability for a global search and increase the convergence speed (1).

<u>Invasive Weed Optimization (IWO):</u>

- It is used to optimize the size of concrete gravity dams to reduce the volume of concrete utilized and construction costs while ensuring significant savings in area (17) (15).

<u>Artificial Bee Colony (ABC) approach:</u>

- This technique has been utilized to improve reservoir and double-arched dam management, providing positive prospects for the most effective water release strategies (17) (1).

<u>Simulated Annealing (SA):</u>

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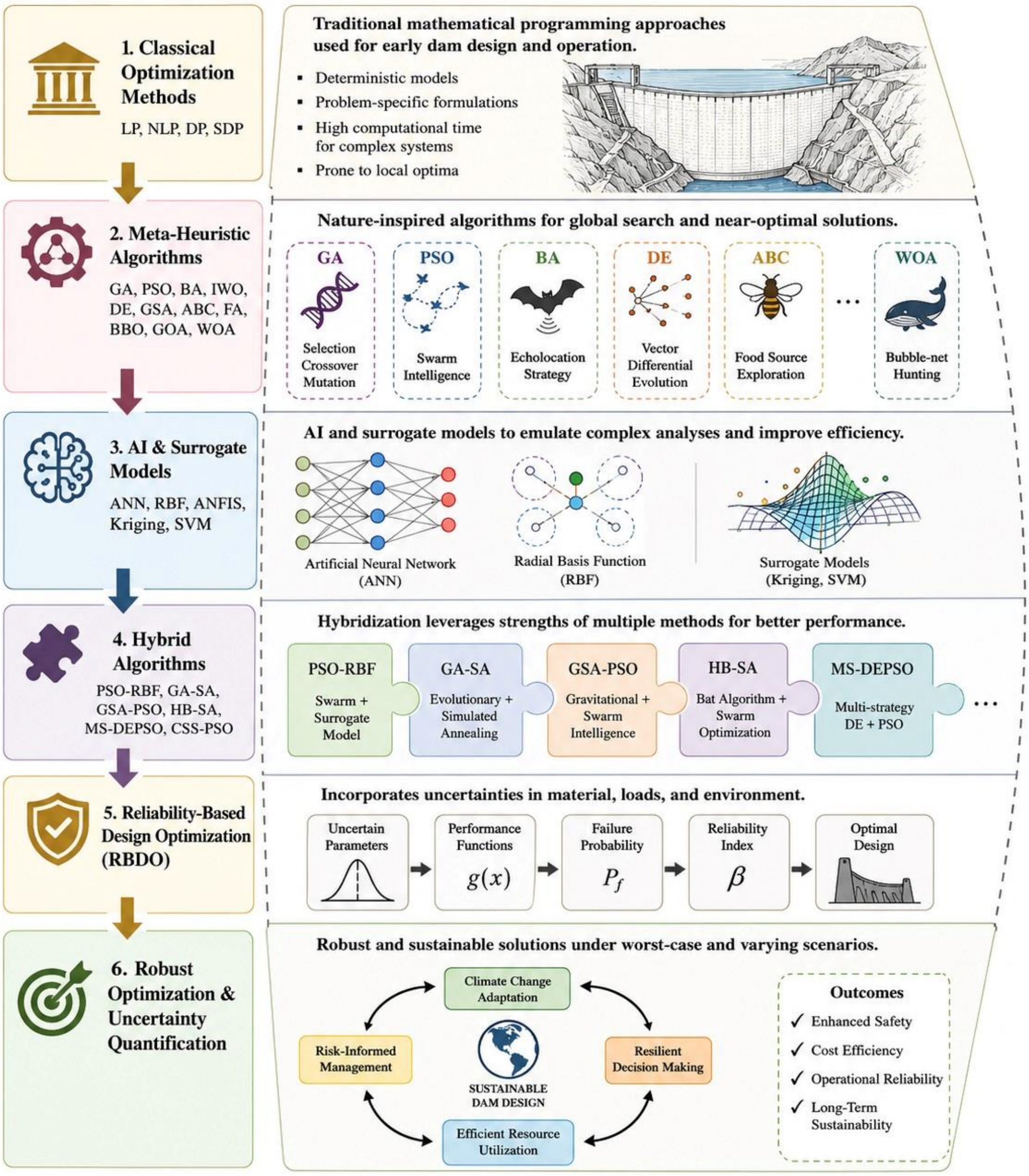

Figure 1: Methods and Strategies for Optimization

- Utilized in the creation of effective reservoir management models, as well as acting as a localized search component in hybrid algorithms (1).

<u>Gravity Search Algorithm (GSA):</u>

- Exhibited competency in solving optimization problems, often achieving results that exceeded the improvements in optimality achieved using Genetic Algorithms (1).

<u>Differential Evolution (DE):</u>

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- Utilized in the advanced engineering of gravity dams, often producing results that exceed those achieved by analytical models (15) (1).

Biogeography-Based Optimization:

- Applied to reservoir operation issues, outperforming GA in some cases (1).

Firefly Algorithm (FA):

- Exhibits effectiveness in reservoir management, achieving superior convergence rates and lower variance when compared to Genetic Algorithms (1).

Grasshopper Optimization Algorithm (GOA):

- Applied to optimal operation of hydropower reservoir systems under climate change (1).

Whale Optimization Algorithm (WOA):

- Applied to support the management of reservoirs, showing effective results (1) (29).

Neural Networks (NN):

- Radial Basis Function (RBF) neural network is used in dam structure optimization for greater accuracy in a shorter time frame (4). It also predicts dam natural frequencies, improving optimization efficiency (26).
- The Back Propagation Neural Network (BPNN) and the Adaptive Neuro-Fuzzy Inference System (ANFIS) are applied to predict operating effectiveness of dams, and thus significantly reduce the computational cost of optimization, especially under seismic loading (1) (22) (24) (13). ANFIS also proves to have better generalization capability in dam behavior prediction than BPNN (22).

Hybrid Algorithms (HAs)

- Hybrid algorithms (HAs) combine the strengths of multiple algorithms to overcome the disadvantages of individual methods, making them highly effective for solving complex water resource management problems and reservoir optimization issues (1). They have consistently shown better results than single meta-heuristic algorithms and traditional methods, and their popularity is growing (1).
- PSO-RBF: Combines Particle Swarm Optimization with Radial Basis Function neural network for dam structure optimization, solving local optimum convergence and achieving high accuracy quickly (4).
- HB-SA (Hybrid Bat-Swarm Algorithm): A new hybrid optimization algorithm built on the BA and PSO, enhancing BA by replacing suboptimal solutions with optimal ones from PSO, thus quickening convergence and avoiding local optima (1).
- GSA-PSO: A hybrid of Gravitational Search Algorithm and PSO for multi-reservoir systems, demonstrating high volumetric reliability index (VRI) (1).
- GA-SA: Hybrid Genetic Algorithm-Simulated Annealing for fuzzy programming of reservoir operation, raising the likelihood of locating an ideal solution while decreasing computation time (1).
- MS-DEPSO: Multi-strategy Differential Evolution and Particle Swarm Optimization hybrid designed to enhance global searchability for reservoir operating policies (1).
- CSS-PSO: A combination of Charged System Search and Particle Swarm Optimization, demonstrating superiority over standard CSS and PSO for arch dam shape optimization under seismic loading (20) .

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Reliability-Based Design Optimization (RBDO)

Reliability-Based Design Optimization (RBDO) is a design improvement methodology in the sense that it adds the uncertainties in the material characteristics, the loads, and the environment and offers a more adequate and robust approach than the deterministic approaches for the optimum design of the concrete gravity dams (16) (10) (11). RBDO optimally balances the overall cost and the safety factors (16).

- Uncertain Parameters: Examines the statistical variability of parameters including specific weight of concrete, bearing capacity of rock mass, properties of sedimentary materials, friction angle, cohesion at the dam-foundation interface, and inefficiencies in the drainage gallery (10).
- Failure Modes: RBDO also takes different failure modes like overturning, sliding, flotation, eccentricity, and failure by bearing capacity (10).
- Governing Failure Mode: The analysis shows that the regulatory failure mode changes in line with the specified reliability index and dam elevation. For the taller dams and high target reliabilities, sliding often controls the design aspects such that the cohesion and friction slope at the base of the dam prevail. However, for lower dams and smaller reliabilities, eccentricity can control such that base length, the specific weight of the concrete, and the ineffectiveness of the drainage gallery become important (10).
- Computational Efficiency: Methodologies such as Subset Simulation utilizing Markov Chain Monte Carlo (MCMC) sampling and advanced metamodels (for instance, Support Vector Machine - SVM) are implemented to effectively assess failure probability while minimizing sample size, thereby lowering computational expenditures (16). Additionally, the Single-Loop Approach (SLA) is applied to maintain computational costs within reasonable limits for determining optimal placements of dam bases and drainage galleries (10).
- Robust Optimization (RO): It is one of the forms of optimization for uncertainty in which one tries to find an optimized design relatively insensible in the face of uncertainty. Like RBDO, RO does not assume the accuracy in the distribution of the uncertain data. So the obtained results are more conservative. It also assures safe and reliable performance under worst-case scenarios (11).

4. CONSTRAINTS AND OBJECTIVE FUNCTIONS IN DAM OPTIMIZATION

Dam optimization involves careful balancing of achieving defined performance objectives against achieving a defined set of constraints.

4.1. Objective Functions

General aims of dam optimization typically encompass optimization of design as being safe as well as economically prudent. Typically applied objective functions are:

- Reduction of Concrete Volume and Construction Expenditure: This represents a primary goal, particularly in the context of concrete gravity and arch dams, as the volume of materials utilized is intrinsically linked to the overall project costs (12) (11) (14) (17) (16) (19) (6) (24) (22) (10) (20) (23).

- Improvement of Dams' Safety: The dam's proper performance and soundness in its life of operation are key concerns, usually addressed alongside cost savings (6) (13) (12).
- Minimization of Tensile Stress: Particularly, minimization of maximum allowable tensile stress in the dam's make-up constitutes a principal safety design (12) .
- Fighting Shortages in Water Availability: One of the major goals in enhancing reservoir management is bridging the gap that exists in supplying and demanding water (1).
- Power Production Increase: In hydropower dam settings, emphasis mainly encompasses taking initiatives that will boost power generation (1).
- Stress and Deformation Reduction: The maintenance of stress and deformation within admissible quantities is required in order to obtain long-term performance of the dam (12).
- Establishment of Overall Stability: The final need of gravity dam is to establish stability against the whole set of forces (14).

4.2. Constraints

Optimization techniques are used to incorporate different forms of constraints that ensure the performance criteria, viability, and safety of the dam.

<u>Geometric constraints:</u>

The parameters that define the physical dimensions and proportions of the dam are:

- Dam slope (5)
- Thickness variations occur in both the horizontal and vertical directions (19)
- Crest size, width, and height measurements. (14) (3)
- The angles involved in overhangs and undercuts (30)
- Primarily, the conventional approach applied to arch dams (30) (6)

<u>Stress Constraints:</u>

Such variables specify the constraints placed upon the stresses acting on the dam and the underlying foundations.

- The maximum tensile and compressive stress values (12) (17) (20) (31) (24) (19) (22) (5) (30).
- The important parameters of finite element analysis related to stress were hypothesized, including the tensile stress zone measurements on the upstream face of the gravity dams (4).
- Ensuring the levels of stresses at every point within the dam and at the foundation remain within allowable limits (17).

<u>Stability Constraints:</u>

These ensure the dam's overall stability against various failure modes.

- Stability of dam slopes (5)
- Sliding stability (14) (6) (20) (31) (10) (5)
- Overturning, flotation, eccentricity, and bearing capacity failure modes, particularly important in reliability-based design (10)
- Cracking resistance

<u>Displacement Constraints:</u>

Enforcing limitations on the allowable deflections for dam parts to ensure compliance with

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design requirements (5)

Frequency Constraints:

Applying frequency constraints on natural frequencies to improve dynamic performance and avoid resonance, especially in the case of seismic loads (8)

Realistic Construction Conditions:

Incorporation of the variables like construction stages, shear stress in lift joints, and minimum tensile stresses inside the monolithic structure is required to reflect realistic construction conditions (3).

Foundation Properties:

It is critical to determine that the dam design suits the mechanical properties (including strength and deformability) and the geological conditions within the foundation rock (10) (32).

Load Conditions:

It is important to analyze a mixture of loading conditions, such as gravitational, hydrostatic, hydrodynamic, and seismic forces, in establishing safety under the most unfavorable conditions (16) (11) (18) (20) (19) (3) (24) (22) (5) (17).

5. Performance Assessment and Related Challenges

Verification of the performance of new dam design and how they work is essential in validating methodology and making it work in practice. Different challenges belong in this category.

5.1. Performance Evaluation Criteria

A parameter set is employed in optimality studies for the assessment of the suggested methodology and the achieved design effectiveness and relevance:

Statistical Measures

- Root Mean Square Error (RMSE): A popular and reliable measure indicating the standard deviation between estimated and observed values; closer to zero indicates less deviation. Mean Absolute Error (MAE) represents the average of the absolute differences between the observed and the modeled values (1).
- Ensuring stress at any point of the dam and foundation does not exceed the allowable limit (1)
- The Coefficient of Determination (R^2) is used as an indicator to determine the effectiveness of a statistical model in that values approaching one indicate the excellence in model performance (1).
- The Nash–Sutcliffe Efficiency (NSE) is a key measure in the field of water engineering, which is mainly used for assessing the predictive skill of models; scores close to one indicate high accuracy (1).

Table 1 consolidates representative dam optimization studies discussed in this review, cross-referencing dam type, algorithm, objective function, governing constraints, and reported performance gains, to allow direct comparison across the literature.

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Table 1: Comparative summary of representative dam optimization studies.

Dam Type	Algorithm(s)	Objective Function	Key Constraint(s)	Reported Improvement	Case Study / Source
Concrete Gravity	GA	Minimize cross-section volume	Stress, sliding/overturning stability	11.9% volume saving; >20% cross-section area saving	(33)
Concrete Gravity	IWO	Minimize concrete volume/cost	Geometric, stability	7.7% volume saving	Koonya Dam, India (34)
Concrete Gravity	RBDO (Subset Simulation + SVM)	Minimize cost for target reliability index	Sliding, overturning, eccentricity, bearing capacity	Identifies governing failure mode vs. dam height/reliability	(35) (36)
Concrete Arch	GA / Hermit Splines + SQP	Minimize concrete volume; preserve	Stress, geometric, construction stages	Up to 17.4% capacity reduction	Karun IV, Iran (37)

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Dam Type	Algorithm(s)	Objective Function	Key Constraint(s)	Reported Improvement	Case Study / Source
		stability			
Concrete Arch	CSS-PSO	Shape optimization under seismic loading	Frequency, stress	Outperforms standalone CSS and PSO	(38)
Concrete Arch	PSO / IPSO + ANFIS	Shape optimization; structural prediction	Stress, stability, frequency	Reduced tensile stress 1.95→1.16 MPa	(39) (40)
Concrete Arch	Kriging-GA (surrogate-assisted)	Shape optimization	Stress, geometric	Reduced FE evaluations / computation time	Jiancaogou Dam, China (41)
CFRD / Earth Dams	GA	Minimize cost; safety-related expenditure	Stability, stress, displacement	Steeper slopes, wider downstream sections at lower cost	Jishixia CFRD, China (42)
Reservoir Operation	Hybrid algorithms (GA-SA, GSA-PSO, MS-DEPSO)	Maximize benefit; minimize deficit	Water balance, hedging policy	Hybrids = 18.7% of 76 reviewed studies; outperform single MH/classical methods	Karun 4, Voshmgir, Golestan (43)

<u>Hydrological Performance Indicators (for Reservoir Operation):</u>

- The Volumetric Reliability Index (VRI) is a measure of how much released water meets demand downstream; high values are desirable (1).
- The resiliency index measures the rate at which the system restores its operability after it has failed, and larger values are desired (1).
- Vulnerability Index: Indicates the system's susceptibility to failure (1).

<u>Computational Efficiency:</u>

Measured by factors such as convergence rate and CPU time (1). Hybrid algorithms, for instance, are particularly valued for their reduced convergence and computation time (1).

5.2. Challenges in Dam Optimization

Despite major improvements, there are still many challenges remaining in the efficient and effective optimization of dams:

a) High Computational Cost: Numerical optimization methods, especially those involving complicated dynamic computations like fluid-structure interaction or time-dependent loading by way of Finite Element Analysis (FEA), require several iterations in structural analysis, thus leading to high computational costs (22) (11) (24) (13) (3) (29). The problem becomes extremely severe for large structures that are defined by a large number of degrees of freedom.

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b) Overcoming Local Optima Constraints: Traditional optimization methods, when combined with varied meta-heuristic methods, often fall into the trap of local optima, thus preventing the determination of the actual global optimum solution (5) (4).
c) Issues in High-Dimensional Nonlinear Optimization: The large number of optimal design parameters, in addition to the inherently nonlinear nature often found in mechanics of dams, provides for optimization challenges that are linked to high dimensionalities (1).
d) Data Accuracy and Relevant Uncertainties: The validity of the optimization analyses to a great extent depends on the confidence level in the input data, for example, the hydrological, meteorological, and geological data. Apart from this reality, the inherent uncertainties involved in the material properties, the boundary conditions (water levels, the ground motions' parameters and temperatures) and the environment create major challenges (2) (10) (11) (16).
e) Algorithm Selection: The heightened use of meta-heuristic algorithms renders the selection of the best-suited algorithm to tackle particular dam optimization problems a significant challenge. Usually, coming to a definitive conclusion as to the best algorithm implies making a comparative analysis (1).
f) Physical Implications and Interval Segmentation: The major deficiency found in the literature that has hitherto been formulated in structural health monitoring (SHM) is the incapability of taking into account physical implications and associated interval segmentation; both these features are applicable to the evaluation of the health state of dams (2).
g) Information Fusion: The integration of information from different monitoring sources (e.g., displacement, cracks, uplift pressure, temperature) for general health evaluation is yet an unsolved task (2).

6. FUTURE DIRECTIONS

To carry the work on dam optimization one stage ahead, several areas have to be investigated and developed:

a) Enhanced Computational Efficiency: Development of advanced computational techniques and regulating protocols reduces the time and capital expenditure on analysis (1) (24) (27). The scope covers the development of advanced approximation models like Kriging and neural networks and their incorporation within the framework of the optimization algorithm (22) (24) (13) (2).
b) Complete Uncertainty Representation: There should be substantial effort to fully define and incorporate uncertainties, especially for the ground motion parameters in RBDO systems. Additionally, building robust optimization methods that provide reliable designs that can accommodate all possible scenarios resulting from an uncertainty range regardless of specific distributions is crucial (13).
c) Localized Parameter Identification: Future research activities should focus on determining mechanical parameters specific to specific sections of dam-foundation systems, instead of using aggregate or equivalent parameters for the whole system, with the view to improving the accuracy of analysis and design (29).

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d) Complex Dam Configurations: Extension of optimization methods to cover more complex arch dam geometries (e.g., double-curvature shapes, asymmetrical configurations, or configurations defined by specific geological features) will greatly enhance their real-world usefulness (27) (12).
e) Advanced AI Use for Health Monitoring: Thorough work must be conducted on model parameter calibration, simulation function, and application of Artificial Intelligence (AI) models to various flow regimes in order to enhance dam health monitoring and diagnosis. This includes developing more physically meaningful monitoring models that can assess and predict long-term dam displacement (29).
f) Refining and Comparison of Algorithms: Developing new meta-heuristic algorithms and extensions, and on-going comparative validation will define the best tools for specific dam optimization problems (29).

7. CONCLUSIONS

The journey to dam optimization has evolved a long distance from tiresome trial-and-error approaches to sophisticated computational methods. This has been so in order to attend to the inherent complexities, high cost, and sheer safety demands of such pivotal hydraulic installations. Major developments have revolved around the implementation of meta-heuristic algorithms such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Invasive Weed Optimization (IWO), to name a few (1) (14) (15) (7) (5). These algorithms have proven to be more effective, quicker, and more precise at giving near-optimal solutions, particularly to non-linear and high-dimensionality problems that have continued to evade conventional methods (1). This promise has been emphasized with the introduction of hybrid algorithms that bring together the positives of both approaches to deliver even improved results under more complicated situations (1). The most important innovation in dam design is the application of Reliability-Based Design Optimization (RBDO) and robust optimization (16) (10) (13). These frameworks deal with uncertainties in material properties, loads, and environmental conditions explicitly, extending beyond deterministic designs for the better trade-off between cost and safety (16). It is in this way that one can analyze and calculate optimal designs that are robust with respect to real-world variability and potential failure mechanisms such as sliding, overturning, and eccentricity (10).

Classical optimization objectives remain the minimization of construction cost, concrete volume and the maximization of dam safety, subject to a dense set of geometric, stress, stability, and frequency constraints (16) (14) (13) (7) (6) (12). Performance is measured in terms of a composite of statistical measures and hydrological measures to guarantee the validity of optimized solutions (1). Despite these advances, the problems of high computational expense, possibility of convergence to local optima, and problems in integrating various data sources for overall health monitoring continue (13) (5) (24) (29) (3). Future research will necessitate further emphasis in continued improvements of more efficient algorithms, more efficient methods of quantifying uncertainty, and solutions to particular problems in devising more elaborate dam building conditions and dam operating conditions. In such improvements, dam engineering as a profession will continue to provide more secure, more affordable, and long-lasting hydro infrastructure to future generations.

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9. COMPETING INTERESTS

The authors declare that they have no known competing financial interests that could have appeared to influence the work reported in this paper.

10. AUTHOR CONTRIBUTIONS

Paudel, A. conceptualized the research, collected data, and wrote the manuscript; Chhetri, S. helped in data collection and refined the article. All authors contributed critically to the draft and gave final approval for publication.

REFERENCES

1. Beiranvand B, Ashofteh PS. A systematic review of optimization of dams reservoir operation using meta-heuristic algorithms. *Water Resour Manag*. 2023;**3457–3526**.
2. Gu H, Yang M, Gu C, Fang Z, Huang X. A comprehensive evaluation method for concrete dam health state combined with gray-analytic hierarchy-optimization theory. *Struct Health Monit*. 2022;**21**(2):250–63.
3. Akbari J, Ahmadi MT, Moharrami H. Advances in concrete arch dams shape optimization. *Appl Math Model*. 2011;**35**(7):3316–33.
4. Li Fan, Qie SBZ, Wu TCX, Gao FDP. A method based on PSO-RBF for optimization of dam structure. *Proc Chin Control Decis Conf (CCDC)*. 2011;**2**:1846–50.
5. Li Y, Wang J, Xu Z. Design optimization of a concrete face rock-fill dam using genetic algorithm. *Math Probl Eng*. 2016;**2016**.
6. Zhang X-fei, Li S-yi, Chen Y-long. Optimization of geometric shape of Xiamen arch dam. *Adv Eng Softw*. 2009;**40**(2):105–9.
7. Li SH, Jing L, Zhou QJ. Shape optimization of concrete gravity dam based on GA-APDL. *ICMTMA*. 2010;**3**:982–5.
8. Salajegheh J, Salajegheh E, Seyedpoor SM, Gholizadeh S. Optimum design of arch dams using simultaneous perturbation stochastic approximation and genetic algorithms. *Civil-Comp Proc*. 2007;**87**.

[DOI: 10.22068/ijoce.2026.16.3.673]

9. Chiti H, Khatibinia M, Akbarpour A, Naseri HR. c r v i h o e f c f. *Vol 6*. 2016;**6**(3):329–48.
10. Siacara AT, Pellizzer GP, Beck AT, Futai MM. Reliability-based design optimization of a concrete dam. *Rev IBRACON Estrut Mater*. 2022;**15**(5):1–20.
11. Fengjie T, Lahmer T. Shape optimization of arch-type dams under uncertainties. *Eng Optim*. 2018;**50**(9):1470–82.
12. Pouraminian M, Ghaemian M. Multi-criteria optimization of concrete arch dams. *Sci Iran*. 2017;**24**(4):1810–20.
13. Tan F, Lahmer T. Shape design of arch dams under load uncertainties with robust optimization. *Front Struct Civ Eng*. 2019;**13**(4):852–62.
14. Araújo LJ, Vieira AA. Cross-section optimization of concrete gravity dams using genetic algorithms. *Proc CILAMCE*. 2017.
15. Ferdowsi A, Hoseini SM, Farzin S, Faramarzpour M, Mousavi SF. Shape optimization of gravity dams using a nature-inspired approach. *J Soft Comput Civ Eng*. 2020;**4**(3):65–78.
16. Chiti H, Khatibinia M, Akbarpour A, Naseri HR. c r v i h o e f c f. *Vol 6*. 2016;**6**(3):329–48.
17. Ghiasi V, Moghadam MA, Koushki M. Optimization of invasive weed for optimal dimensions of concrete gravity dams. *J Soft Comput Civ Eng*. 2022;**6**(4):95–111.
18. Khiavi MP, Ghorbani MA, Rahmati AG. Seismic optimization of concrete gravity dams using a rubber damper. *Int J Acoust Vib*. 2020;**25**(3):425–35.
19. Grigorov S, Tasev S, Tzenkov A, Fanelli M, Gunn RM. Arch dam shape optimization procedure accounting for dam seismic response. *Undefined*. 2009;2–5.
20. Kaveh A, Mahdavi VR. Shape optimization of arch dams under earthquake loading using meta-heuristic algorithms. *KSCE J Civ Eng*. 2013;**17**(7):1690–9.
21. Pourbakhshian S, Ghaemian M, Joghataie A. Shape optimization of concrete arch dams considering stage construction. *Sci Iran*. 2016;**23**(1):21–35.
22. Hamidian D, Seyedpoor SM. Shape optimal design of arch dams using adaptive neuro-fuzzy inference system and improved particle swarm optimization. *Appl Math Model*. 2010;**34**(6):1574–85.
23. Wassermann K. Three-dimensional shape optimization of arch dams with prescribed shape functions. *J Struct Mech*. 1983;**11**(4):465–89.
24. Seyedpoor SM, Salajegheh J, Salajegheh E, Gholizadeh S. Optimum shape design of arch dams for earthquake loading using fuzzy inference system and wavelet neural networks. *Eng Optim*. 2009;**41**(5):473–93.
25. Takalloozadeh M, Ghaemian M. Shape optimization of concrete arch dams considering abutment stability. *Sci Iran A*. 2014; 1297–308.
26. Gholizadeh S, Seyedpoor SM. Shape optimization of arch dams by metaheuristics and neural networks for frequency constraints. *Sci Iran*. 2011;**18**(5):1020–7.

[DOI: 10.22068/ijoce.2026.16.3.673]

27. Wang YQ, Zhao RH, Liu Y, Chen YZ, Ma XY. Shape optimization of single-curvature arch dam based on sequential Kriging-genetic algorithm. *Appl Sci*. 2019;**9**(20).
28. Bofang Z, Bin R, Jinsheng J, Yisheng L. Shape optimization of arch dams for static and dynamic loads. *J Struct Eng*. 1992;**118**.
29. Lin C, Li T, Chen S, Lin C, Liu X, Gao L, et al. Structural identification in long-term deformation characteristic of dam foundation using meta-heuristic optimization techniques. *Adv Eng Softw*. 2020;**148**:102870.
30. Duan Y, Yuan W, Liu HB. Shape optimization for arch dam with sequential quadratic programming method. *Appl Mech Mater*. 2014;**580–583**:1961–65.
31. Pourbakhshian S, Ghaemain M. Shape optimization of arch dams using sensitivity analysis. *KSCE J Civ Eng*. 2016;**20**(5):1966–76.
32. Fan Q, Zhou S, Yang N. Optimization design of foundation excavation for Xiluodu super-high arch dam in China. *J Rock Mech Geotech Eng*. 2015;**7**(2):120–35.
33. Li SH, Jing L, Zhou QJ. Shape optimization of concrete gravity dam based on GA-APDL. *ICMTMA*. 2010;**3**:982–5.
34. Ghiasi V, Moghadam MA, Koushki M. Optimization of invasive weed for optimal dimensions of concrete gravity dams. *J Soft Comput Civ Eng*. 2022;**6**(4):95–111.
35. Chiti H, Khatibinia M, Akbarpour A, Naseri HR. c r v i h o e f c f. *Vol 6*. 2016;**6**(3):329–48.
36. Siacara AT, Pellizzer GP, Beck AT, Futai MM. Reliability-based design optimization of a concrete dam. *Rev IBRACON Estrut Mater*. 2022;**15**(5):1–20.
37. Akbari J, Ahmadi MT, Moharrami H. Advances in concrete arch dams shape optimization. *Appl Math Model*. 2011;**35**(7):3316–33.
38. Kaveh A, Mahdavi VR. Shape optimization of arch dams under earthquake loading using meta-heuristic algorithms. *KSCE J Civ Eng*. 2013;**17**(7):1690–9.
39. Zhang X-fei, Li S-yi, Chen Y-long. Optimization of geometric shape of Xiamen arch dam. *Adv Eng Softw*. 2009;**40**(2):105–9.
40. Hamidian D, Seyedpoor SM. Shape optimal design of arch dams using adaptive neuro-fuzzy inference system and improved particle swarm optimization. *Appl Math Model*. 2010;**34**(6):1574–85.
41. Wang YQ, Zhao RH, Liu Y, Chen YZ, Ma XY. Shape optimization of single-curvature arch dam based on sequential Kriging-genetic algorithm. *Appl Sci*. 2019;**9**(20).
42. Li Y, Wang J, Xu Z. Design optimization of a concrete face rock-fill dam using genetic algorithm. *Math Probl Eng*. 2016;**2016**.
43. Beiranvand B, Ashofteh PS. A systematic review of optimization of dams reservoir operation using meta-heuristic algorithms. *Water Resour Manag*. 2023;**3457–3526**.

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