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Data-Driven Inverse Analysis for Deformation Management of Concrete Face Rockfill Dams: A Literature Review

CAO NING[1], Ts. Dr. Nurazim Ibrahim[2]
1,2Faculty Of Engineering And Technology Infrastructure, Kuala Lumpur University of Science and Technology,
43000 Kajang, Selangor, Malaysia
Corresponding Author: Cao ning

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ABSTRACT:
With the increasing scale and complexity of hydraulic infrastructure projects, effective deformation management of concrete face rockfill dams (CFRDs) has become a core concern in dam safety governance and engineering decision-making. Traditional deformation analysis methods rely heavily on deterministic numerical models and empirical parameter selection, which are often insufficient to capture the inherent nonlinearity, uncertainty, and time-dependent behavior of rockfill materials. In recent years, data-driven inverse analysis methods, supported by deformation monitoring systems and intelligent algorithms, have emerged as a promising research direction.

This paper systematically reviews the existing literature on data-driven inverse analysis for CFRD deformation management from a management-oriented perspective. The review is conducted along three dimensions: the conceptual evolution and managerial significance of inverse analysis in dam engineering; the methodological development of inverse analysis techniques, including numerical modeling, stochastic approaches, and intelligent optimization; and the mechanisms through which data-driven inverse analysis enhances deformation risk management and decision support. Existing studies are further synthesized into a project–system–managerial analytical framework.

The review identifies several limitations in current research, including fragmented methodological perspectives, insufficient integration between technical analysis and management decision-making, and a lack of systematic frameworks for long-term deformation governance. Accordingly, future research directions are proposed, emphasizing integrated analytical perspectives, heterogeneity-oriented management analysis, and systematic decision-support mechanisms. This study aims to provide theoretical references and managerial insights for advancing data-driven deformation management of CFRDs.

KEYWORDS: Concrete Face Rockfill Dam; Deformation Management; Inverse Analysis; Data-Driven Methods; Engineering Decision Support .

I. INTRODUCTION

Concrete face rockfill dams (CFRDs) are widely adopted in large-scale water conservancy and hydropower projects due to their economic efficiency, adaptability to complex geological conditions, and favorable construction performance. However, CFRDs exhibit pronounced nonlinear deformation characteristics and significant time-dependent behavior during construction, impoundment, and long-term operation. Excessive deformation not only affects structural safety but also complicates reservoir operation, maintenance planning, and risk governance.

From an engineering management perspective, deformation behavior constitutes a key performance indicator reflecting the comprehensive effects of material properties, construction quality, environmental conditions, and operational strategies. Modern dam safety management increasingly relies on numerical simulation and monitoring-based assessment to support decision-making. Nevertheless, the reliability of such decision-support tools is highly sensitive to model parameters, which are often uncertain, scale-dependent, and difficult to determine accurately through laboratory testing alone.

Inverse analysis provides an effective pathway to bridge monitoring data and numerical models by identifying model parameters through observed deformation responses. With the rapid development of monitoring technologies and intelligent algorithms, data-driven inverse analysis has attracted growing attention in dam engineering research. While a substantial body of literature has emerged, existing studies remain fragmented in terms of methodological focus and managerial interpretation. In particular, the integration of inverse analysis results into deformation risk management and decision-support frameworks has not been systematically reviewed.

Against this background, this paper conducts a comprehensive literature review on data-driven inverse analysis for CFRD deformation management, aiming to synthesize existing research, clarify underlying mechanisms, and identify future research directions from a management-oriented perspective.

II. CONCEPTUAL FOUNDATIONS OF INVERSE ANALYSIS IN DEFORMATION MANAGEMENT

2.1 From Deterministic Analysis to Data-Driven Management

Traditional deformation analysis of CFRDs is primarily based on deterministic numerical modeling, where constitutive parameters are selected according to laboratory tests, engineering experience, or empirical correlations. While such approaches provide initial guidance, they often fail to reflect the actual in-situ behavior of large-scale rockfill dams due to scale effects, material heterogeneity, and simplifications inherent in idealized models.

Inverse analysis introduces a paradigm shift by treating deformation monitoring data as a core input for model calibration. It systematically reduces the gap between predictions and real-world measurements through iterative parameter identification and optimization. From a management standpoint, inverse analysis transforms deformation monitoring from a passive safety-checking tool into an active knowledge-generation mechanism, enabling more informed decision-making and long-term performance assessment. This shift significantly enhances the informational value and utility of structural health monitoring systems throughout the dam's lifecycle.

2.2 Managerial Significance of Inverse Analysis

Beyond its foundational technical role, inverse analysis carries profound and multifaceted managerial implications. By systematically reducing parameter uncertainty and significantly improving the predictive reliability of computational models, inverse analysis strengthens the scientific basis for critical decisions. It thereby enhances the credibility and defensibility of simulation-based decision support systems, fostering greater confidence among stakeholders. This capability is particularly valuable in the context of long-term deformation management of large-scale infrastructures, such as dams and tunnels, where strategic decisions related to reservoir operation protocols, inspection scheduling, maintenance prioritization, and risk mitigation strategies must be made under considerable uncertainty. The method provides a structured framework for transforming monitoring data into actionable insights, enabling managers to optimize resource allocation, justify investments in safety measures, and ultimately ensure operational resilience over the full lifecycle of a project.

III.METHODOLOGICAL DEVELOPMENT OF INVERSE ANALYSIS FOR CFRDs

3.1 Numerical-Model-Based Inverse Analysis

Early studies on inverse analysis in dam engineering primarily focused on direct iterative calibration of numerical models, with particular emphasis on widely used constitutive formulations such as the Duncan–Chang E–B model for simulating nonlinear stress-strain relationships in fill materials, as well as various rheological models developed to represent time-dependent deformations and seepage behaviors. Although theoretically sound and effective in principle, these early methodologies often required substantial computational resources and lengthy execution times, making them difficult to deploy in time-sensitive engineering contexts. Moreover, due to their reliance on gradient-based or trial-error optimization schemes, they were highly susceptible to converging to local optima rather than the global solution, especially in cases involving high-dimensional parameter spaces or strong non-uniqueness of material properties. Such limitations considerably restricted their practical applicability in real-world dam safety management and monitoring scenarios, where robustness, interpretability, and operational efficiency are critical.

3.2 Stochastic and Probabilistic Approaches

To address the pervasive issue of uncertainty in various engineering and scientific domains, such as structural analysis and geomechanics, researchers have introduced advanced computational techniques, including stochastic finite element methods and probabilistic inverse analysis frameworks. These approaches explicitly account for parameter variability by incorporating probability distributions into models, thereby enabling more realistic simulations that

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yield probabilistic deformation predictions rather than deterministic outcomes. From a management perspective, probabilistic outputs are highly valuable for risk-based decision-making, as they facilitate the assessment of potential failures and the optimization of safety margins; however, their high computational cost, arising from the need for numerous simulations like Monte Carlo sampling, remains a major challenge that limits widespread practical application.

3.3 Intelligent and Data-Driven Inverse Analysis

Recent studies have demonstrated a significant shift towards the adoption of advanced intelligent optimization and machine learning techniques, including genetic algorithms, support vector regression, and swarm intelligence, to enhance inversion efficiency across various disciplines such as geophysics, engineering, and environmental science. This trend is driven by the need to handle complex, high-dimensional problems more effectively. Hybrid frameworks that combine surrogate models, which serve as efficient approximations of computationally expensive systems, with sophisticated optimization algorithms have proven particularly impactful. These integrations substantially reduce the computational burden associated with traditional methods and enable near-real-time analysis, thereby supporting rapid decision-making in dynamic environments. Furthermore, these developments signify a crucial advancement in the field, marking a transformative step toward the practical, management-oriented application of inverse analysis, where real-world constraints and operational efficiency are paramount.

IV.DATA-DRIVEN INVERSE ANALYSIS AND DEFORMATION RISK MANAGEMENT

4.1 Project-Level Applications

At the project level, inverse analysis significantly enhances the consistency between simulated and observed deformation by continuously calibrating numerical models with real-time monitoring data. This process allows for more accurate and reliable evaluation of dam performance throughout critical phases such as construction and long-term operation. By reducing uncertainties in parameter estimation and model predictions, this capability directly supports the early identification of potential deformation-related risks. Furthermore, it enables engineers to implement proactive control measures, thereby improving the overall safety and sustainability of the structure.

4.2 System-Level Integration

At the system level, data-driven inverse analysis employs sophisticated computational techniques to facilitate the seamless integration of monitoring data, numerical models, and management platforms. This process enhances the interoperability between various system components, allowing for efficient data assimilation and model calibration. Such integration robustly supports continuous performance assessment by providing real-time insights and predictive analytics, thereby enabling adaptive management strategies that can proactively address operational challenges and optimize system resilience.

4.3 Managerial-Level Decision Support

At the managerial level, inverse analysis outputs provide essential quantitative support for decision-making under uncertainty. These outputs enable leaders to evaluate various scenarios, quantify potential risks, and assess the implications of different strategic choices. By translating complex technical results into accessible risk indicators and performance metrics, inverse analysis bridges the gap between detailed engineering insights and executive oversight. This strengthened linkage facilitates more informed and transparent governance, enhances accountability, and supports the alignment of technical projects with broader organizational goals. As a result, management can prioritize resources more effectively, mitigate unforeseen challenges, and drive operational excellence with greater confidence.

V.RESEARCH GAPS AND FUTURE DIRECTIONS

Despite significant progress, several limitations remain in the existing literature, pointing to critical gaps that need to be addressed in future studies.

First, research perspectives remain fragmented. Most studies focus either on methodological innovation or case-specific applications, lacking an integrated framework that effectively connects inverse analysis with broader deformation management objectives. This disconnect hinders the development of generalizable strategies that can be adapted across various scenarios and limits the practical applicability of research outcomes in real-world settings.

Second, heterogeneity analysis is insufficient. Differences among dams — such as variations in scale, construction stage, material composition, and operational conditions—are rarely examined systematically from a management perspective. This oversight results in models and solutions that may not be transferable or scalable, reducing their relevance for diverse dam safety management contexts.

Third, mechanism research remains underdeveloped. Although inverse analysis is often proposed as a tool for improving decision-making, the pathways through which it enhances decision quality and risk governance are frequently implicitly assumed rather than explicitly analyzed. There is a notable lack of empirical and theoretical exploration into how inverse analysis contributes to more robust and adaptive governance structures.

Future research should therefore advance along three complementary directions: developing integrated analytical frameworks that effectively link technical methods with management objectives; promoting heterogeneity-oriented studies that account for different dam contexts and conditions; and undertaking systematic exploration of the underlying decision-support mechanisms to better understand how inverse analysis translates into improved safety outcomes.

V. Conclusion

This paper provides a comprehensive systematic literature review of data-driven inverse analysis for deformation management of concrete face rockfill dams (CFRDs) from a management-oriented perspective. It examines the application of inverse analysis techniques in monitoring, predicting, and controlling deformation behavior in CFRDs throughout their lifecycle. By synthesizing conceptual foundations, methodological developments, and managerial mechanisms, the study highlights the growing role of inverse analysis in supporting deformation risk governance and engineering decision-making. The review further discusses the integration of monitoring data, numerical modeling, and optimization algorithms to improve the accuracy of inverse identification of material parameters and deformation predictions. Additionally, it identifies key research gaps in areas such as multi-source data fusion, uncertainty quantification, and real-time inverse analysis, and proposes future directions to enhance the integration of data-driven analysis and infrastructure management, including the adoption of machine learning and digital twin technologies.

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