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EDITOR **ASSOC. PROF. DR. ENGİN ÖZDEMİR**

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CONTENTS

Chapter 1

A MULTI-HAZARD, PERFORMANCE-CENTERED FRAMEWORK FOR CLIMATE-RESILIENT CONSTRUCTION MANAGEMENT

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1. Introduction

1.1 Background and Motivation

The construction sector functions as a complex, multi-risk socio-technical system—integrating labor, materials, machinery, and governance under dynamic and often unpredictable environmental conditions (Czajkowska & Ingaldi, 2025). Unlike controlled industrial production, construction activities are predominantly conducted outdoors, are labor-intensive, and are geographically dispersed, making them acutely sensitive to external stressors.

In recent years, the convergence of climate change impacts, seismic and disaster risks, and sustainability transition pressures has significantly reshaped the risk landscape facing construction projects. These risks are no longer isolated or episodic; rather, they interact in ways that amplify disruption and challenge traditional project delivery models (Lucanto et al., 2024).

Among these, climate-induced heat stress has emerged as a persistent operational constraint. Rising ambient temperatures and the increasing frequency of heatwaves have been shown to reduce labor productivity, elevate safety risks, and disrupt construction scheduling. A recent meta-analysis confirmed that heat exposure significantly impairs productivity once critical thermal thresholds are exceeded, resulting in cascading effects on project duration and cost stability (Han et al., 2025). Climate stress, therefore, is not merely a background environmental variable—it is a direct and measurable determinant of construction system performance.

Simultaneously, earthquakes and other disaster-related shocks impose abrupt and severe disruptions. Beyond the immediate physical damage, seismic events interrupt construction activities, delay project timelines, and necessitate prolonged recovery and reconstruction phases. Emerging research emphasizes that disaster outcomes are shaped not only by hazard intensity but also by the quality of construction, structural vulnerabilities, and deficiencies in risk-informed decision-making (Liu et al., 2024; Oğuz & Hansu, 2025b). Poor retrofitting practices and weak governance capacity further exacerbate post-disaster performance losses.

In parallel, the construction industry is under growing pressure to align with circular economy principles and decarbonization targets. As a major contributor to global material consumption, waste generation, and lifecycle emissions, the sector is being called upon to adopt strategies such as modular construction, material reuse, and design-for-disassembly. While these approaches are often promoted for their environmental benefits, they also offer critical resilience advantages—enabling faster post-disaster reconstruction, reducing supply chain dependencies, and enhancing lifecycle adaptability (Rao et al., 2025; Çetin & Kirchherr, 2025).

Importantly, these stressors do not operate in silos. Heat stress can weaken workforce capacity and accelerate material degradation, thereby amplifying vulnerability to seismic damage. Seismic disruptions can delay schedules and fracture material recovery loops, undermining circular construction efforts.

Conversely, circular systems can reduce recovery time, stabilize costs, and improve system resilience under compound risk conditions.

This interdependence underscores the need to move beyond single-hazard thinking and adopt a systems-based perspective that integrates climate stress, disaster risk, and circular performance into a unified project management approach. Yet, despite growing recognition of these converging challenges, practical guidance for construction managers remains fragmented. Current frameworks often treat climate adaptation, seismic safety, and sustainability as parallel policy concerns—limiting their effectiveness in stabilizing construction performance under real-world, multi-hazard conditions.

1.2 Limitations of Existing Literature

Current literature on climate risk, seismic hazard, and sustainability in the construction sector reveals significant structural limitations that hinder the development of integrated, performance-oriented management strategies.

First, research on climate change impacts in construction has primarily centered on thermal stress and labor productivity loss, supported by robust quantitative modeling. However, this body of work often stops short of connecting these findings to real-time project management practices, such as adaptive scheduling, resource allocation, or dynamic workforce planning (Han et al., 2025). As a result, climate stress is treated more as a background risk than an operational decision variable (Oğuz & Hansu, 2025c).

Second, studies in seismic and disaster risk predominantly focus on structural vulnerability, damage propagation, and hazard modeling. While these contributions are foundational for engineering resilience, they typically do not extend into the realm of construction-phase management, leaving a gap in understanding how seismic events affect ongoing projects, work sequencing, or governance coordination (Liu et al., 2024). Empirical evidence from recent earthquakes confirms that project outcomes are often shaped less by hazard intensity than by failures in risk-informed planning and post-disaster governance (Oğuz & Hansu, 2025b).

Third, the emerging literature on circular construction has made substantial progress in addressing material efficiency and environmental performance, particularly through concepts such as modular design, reuse, and lifecycle assessment. However, most of these studies treat circularity as an environmental strategy rather than a risk resilience mechanism, with limited consideration of how circular systems could function under multi-hazard or post-disaster conditions (Çetin & Kirchherr, 2025).

Taken together, these siloed approaches have produced valuable insights but fall short in supporting project-level decision-making under compound, interacting risk conditions. The lack of integration across hazard types, managerial functions, and sustainability strategies limits the sector's ability to transition from reactive hazard response to proactive, resilience-oriented performance management.

Summary of Gaps in the Existing Literature:

Climate literature: Provides strong empirical data on thermal stress, but lacks integration into decision-making tools (e.g., adaptive schedules, climate-informed planning).

Seismic/disaster literature: Advances structural models, but weakly linked to active construction project management and coordination during disruptions.

Circular construction literature: Focuses on environmental efficiency, but rarely addresses circularity's role in resilience or multi-hazard recovery contexts.

These limitations underscore the need for an integrated construction management framework that links climate adaptation, seismic risk reduction, and circular design with real-time project performance and governance control mechanisms.

1.3 Research Gap and Contribution

Despite extensive research on climate impacts, seismic risk, and sustainability in construction, the literature remains fragmented along disciplinary and hazard-specific lines. Climate-focused studies primarily examine heat stress and productivity loss, seismic and disaster research concentrates on structural safety and post-event recovery, and circular construction research emphasizes environmental performance and material efficiency. What is notably absent is an integrated construction management framework that brings these domains together in a manner that is directly actionable at the project level.

Specifically, existing studies do not provide a decision-oriented framework that simultaneously integrates climate-induced stress, seismic and disaster risk, and circular construction strategies, nor do they explicitly link these interacting risks to construction project performance outcomes—such as productivity, schedule reliability, cost stability, and safety—and the managerial decisions that govern them. As a result, construction managers and policymakers lack structured guidance for stabilizing project performance under compound and interacting risk conditions.

This study addresses this gap by developing a conceptual multi-hazard and climate-resilient construction management framework grounded in a structured synthesis of empirical evidence across climate–productivity analysis, seismic risk and damage studies, post-disaster governance research, and circular economy applications in construction. The framework advances two core contributions. First, it introduces a performance-centered integration of climate stress, disaster risk, and circular systems within a unified construction management logic. Second, it establishes governance as the central decision-making and control mechanism, while explicitly positioning circular and digital systems as enabling supports rather than autonomous drivers of project performance.

Rather than seeking to model hazard propagation or empirically validate individual components, the contribution of this study lies in consolidating fragmented knowledge into a coherent, theoretically grounded framework that clarifies causal relationships and managerial roles. By embedding resilience and circularity within a governance-led, performance-oriented structure, the framework provides a foundational reference for future quantitative validation, simulation, and applied implementation in climate-adaptive and risk-informed construction management.

2. Methodological Positioning: Structured Conceptual Synthesis

2.1 Research Design Rationale

This study is positioned as a theory-building and framework-development paper, rather than a narrative review, bibliometric synthesis, or empirical case study. Its central aim is to advance construction management theory by conceptually integrating diverse strands of empirically grounded research—drawn from climate science, seismic risk analysis, disaster governance, and circular construction—into a unified framework capable of informing risk-informed decision-making in complex project environments (Tran et al., 2023).

Construction projects are increasingly exposed to compound and interacting hazards, including chronic climate stressors and acute disaster events, while simultaneously facing mounting pressure to deliver sustainable and low-carbon outcomes. Traditional literature reviews tend to summarize research outputs within disciplinary boundaries but rarely seek to abstract, link, and reconfigure constructs across domains (Kassier, 2024). Such approaches are insufficient for addressing the systemic and interdependent nature of risk in contemporary construction systems.

To overcome this limitation, the study adopts a structured conceptual synthesis methodology, which is particularly suited to theory development in engineering and infrastructure management contexts where empirical evidence is dispersed across siloed literatures (Bayeroju et al., 2024). Structured conceptual synthesis supports the abstraction of core constructs, the identification of cross-domain interdependencies, and the integration of these elements into a coherent theoretical model. In contrast to statistical meta-analysis or bibliometric mapping, this approach focuses on construct-level consolidation rather than quantitative aggregation or publication trend analysis (Hoang, 2025).

To ensure transparency and reproducibility, the structured conceptual synthesis followed an explicit and systematic protocol (Oyewobi et al., 2025). Peer-reviewed literature was identified through targeted searches of Scopus, Web of Science, and Google Scholar, covering the period 2015–2025, corresponding to the rapid expansion of research on climate resilience, disaster risk reduction, and circular construction. Inclusion criteria were limited to peer-reviewed journal articles and high-quality conference proceedings directly related to construction engineering, infrastructure delivery, and construction management, with emphasis on empirically grounded studies and authoritative reviews. Studies focused exclusively on design codes, material chemistry, or non-construction sectors were excluded. The synthesis encompassed five domains: climate-induced productivity and heat stress, seismic risk and structural vulnerability, disaster governance and recovery performance, circular economy applications in construction, and digital risk management technologies. Key constructs—namely hazard exposure, construction project performance, governance response, and enabling systems—were abstracted iteratively through cross-domain comparison and mapped according to their functional roles within construction systems (Bayeroju et al., 2024). No statistical meta-analysis or bibliometric analysis was conducted; instead, empirical findings were consolidated at the conceptual level to develop an integrative, decision-oriented management framework.

By positioning the study as a structured conceptual synthesis with explicit theoretical intent, this research contributes to a growing body of civil engineering and construction management literature that seeks to bridge climate adaptation, disaster resilience, and sustainability through integrated systems thinking. The resulting framework is not presented as a final or prescriptive solution but as a foundational model designed to be further tested, simulated, and refined through future empirical research.

2.2 Evidence Base

The proposed framework is grounded in a structured synthesis of empirically validated research drawn from multiple construction-related domains that collectively address performance disruption under climate and disaster risk. Rather than exhaustively reviewing each domain, this section defines the empirical scope and provenance of the evidence base used to inform construct abstraction and framework development, while detailed conceptual integration is presented in Section 3.

The evidence base spans five interrelated research domains that have demonstrated measurable impacts on construction project performance (Hu et al., 2025). These include: (i) climate-induced productivity and heat stress studies quantifying temperature–performance relationships; (ii) seismic risk, structural vulnerability, and retrofitting research examining damage propagation and recovery trajectories; (iii) disaster governance and post-disaster reconstruction studies identifying institutional determinants of recovery performance; (iv) circular economy research assessing modularity, material reuse, and lifecycle flexibility in construction systems; and (v) digital construction and Industry 4.0 studies evaluating the role of BIM, digital twins, and real-time monitoring in risk-informed decision-making.

Across these domains, empirical findings consistently demonstrate that external hazards and systemic stressors affect construction projects primarily through performance degradation pathways, including productivity loss, schedule disruption, cost instability, and safety risk (Hu et al., 2025). At the same time, the literature highlights that project outcomes are strongly mediated by governance capacity, adaptive planning, and the availability of enabling systems, rather than by hazard intensity alone (Chester et al., 2021). This convergence provides a robust empirical foundation for treating construction projects as adaptive socio-technical systems in which hazards act as exogenous forcing conditions, governance constitutes the primary control mechanism, and circular and digital systems function as performance-supporting enablers (Abdelmegid et al., 2024).

The evidence synthesized in this study is drawn exclusively from peer-reviewed journal articles and high-quality scholarly sources published between 2015 and 2025, ensuring relevance to contemporary construction risk conditions. These sources are mapped to abstracted conceptual roles—hazard exposure, project performance, governance response, and enabling systems—through an iterative synthesis process described in Section 2.3. The resulting conceptual mappings and their empirical origins are summarized in Table 1, which is presented in Section 3 to support the subsequent development of the framework's theoretical architecture.

2.3 Synthesis Logic

The formulation of the Multi-Hazard and Climate-Resilient Construction Management Framework is guided by a structured conceptual synthesis process designed to transform fragmented empirical evidence into a logically coherent theoretical model (Acuña Coll & Sánchez-Silva, 2023). Given the interdisciplinary nature of the domains involved—climate adaptation, seismic risk, disaster governance, and circular construction—this approach enables the abstraction, connection, and integration of core constructs in a manner that supports performance-oriented management under compound risk.

The synthesis follows a three-phase analytical trajectory. First, empirical findings from diverse disciplinary sources are systematically abstracted into generalizable conceptual elements. Constructs such as thermal thresholds for labor productivity, probabilistic seismic vulnerability, governance coordination mechanisms, and circular design principles are identified not in isolation but in terms of their implications for construction system performance—specifically productivity, schedule reliability, cost stability, and safety (Savaş, 2025).

Second, interdependencies across domains are mapped through structured conceptual analysis. This process reveals systemic interactions that are not captured in single-hazard or siloed research (Bianchi, 2023). For instance, climate-induced heat stress reduces workforce output and delays task sequences, which may in turn elevate exposure to seismic risks during critical construction phases. Similarly, digital tools such as Building Information Modeling (BIM) and digital twins not only enable real-time risk monitoring but also facilitate material circularity through supply chain visibility. These cross-domain interactions form the analytical foundation for multi-layered integration.

In the third phase, the abstracted constructs and identified interlinkages are consolidated into a layered framework architecture. This framework organizes external hazards, performance effects, managerial control functions, and enabling systems into discrete but interconnected layers, each defined by its functional role within the adaptive construction system. The framework places construction project performance at the center of analysis, mediating between exogenous hazard pressures and endogenous managerial decisions, while circular and digital systems act as non-autonomous enablers of adaptive capacity. This structure ensures both conceptual integrity and practical relevance for decision-makers managing infrastructure projects under multi-hazard conditions.

The logic and progression of this synthesis process are illustrated in Figure 1, which visualizes the methodological pathway from empirical evidence to theoretical integration. This figure also serves to conceptually bridge the structured synthesis process in this section with the formal presentation of the framework itself in Section 4.

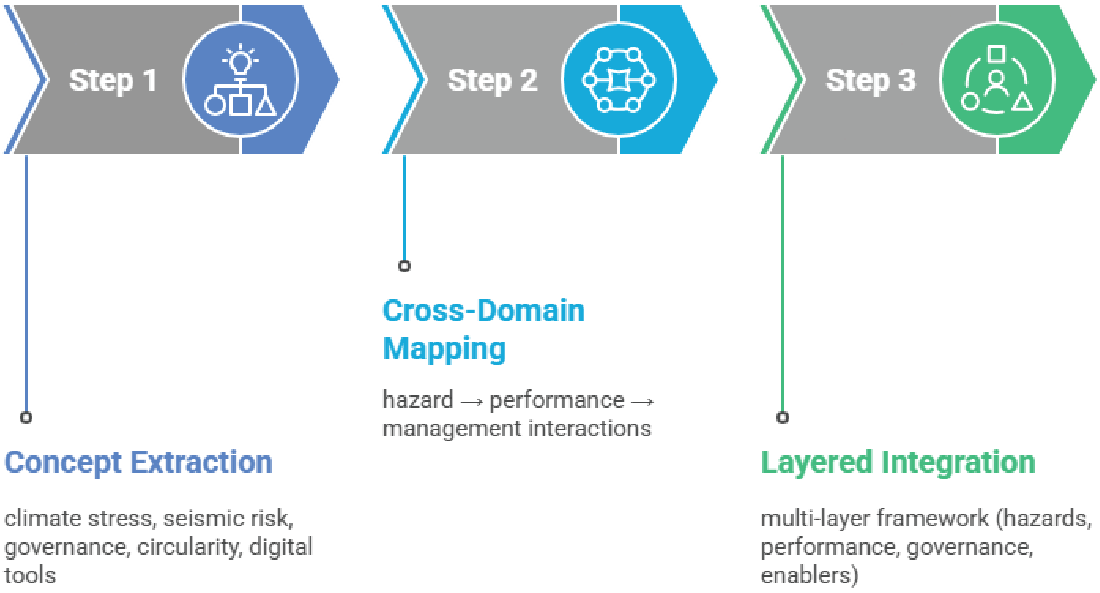

Figure 1. Conceptual Synthesis Process for Framework Development

3. Conceptual Foundations and Empirical Synthesis

This section establishes the conceptual foundations required to integrate climate stress, disaster risk, and circular–digital capabilities into a unified construction management logic. Rather than restating domain-specific evidence, it consolidates empirically grounded constructs into a set of operational definitions and boundary conditions that enable consistent interpretation of the proposed framework and its causal pathways.

At the core of the synthesis is the treatment of construction as an adaptive socio-technical system, where outcomes emerge from interactions among environmental forcing conditions, managerial control, and enabling capabilities (Abdelmegid et al., 2024). Within this framing, hazards and climate stressors (e.g., heat exposure, earthquakes, floods) are defined as exogenous forcing conditions: they generate operational stress and disruption but do not respond to internal project feedback (Amekudzi-Kennedy et al., 2024). "Compound risk" in this study therefore refers to the co-occurrence and interaction of external stressors (e.g., concurrent heat exposure and disruption-related delays), not to endogeneity in which hazards adapt to project performance.

Construction project performance is defined as the central system outcome to be stabilized under multi-hazard exposure, operationalized through four dimensions: productivity, schedule reliability, cost stability, and safety. These indicators are intentionally selected because they represent the dominant managerial performance targets in construction delivery and provide a consistent basis for linking heterogeneous hazards to project outcomes. Importantly, the framework treats resilience as performance continuity and recoverability, rather than as hazard resistance alone, reflecting the shift in resilience thinking toward maintaining function under stress and restoring performance following disruption (Joo & Sinha, 2023).

Management and governance are conceptualized as the sole locus of decision-making and control (Oğuz & Hansu, 2025b). This layer encompasses risk-informed planning, adaptive scheduling, coordination across actors, and recovery governance. The synthesis deliberately avoids distributing decision authority across technological tools or material systems; instead, governance is modeled as the only mechanism capable of initiating and executing control actions that directly alter performance trajectories. This construct is essential for maintaining causal clarity, particularly in multi-actor construction settings where responsibility and accountability must remain traceable to institutional and managerial decisions.

Circular and digital systems are defined as enabling capabilities that support adaptation but do not constitute autonomous control. Circular enablers—such as modularity, material reuse, and design-for-disassembly—strengthen physical recoverability, reduce supply-chain dependency, and improve lifecycle flexibility (Oğuz & Hansu, 2025c). Digital enablers—such as BIM, digital twins, sensing, and analytics—support monitoring, visualization, and scenario evaluation (Hu & Assaad, 2024). In both cases, their role is explicitly supportive: enablers augment governance capacity by improving information quality and implementation feasibility, but they do not initiate decisions or directly control performance. This distinction prevents the common conceptual conflation of "capability" with "authority," which can undermine analytical rigor in resilience frameworks.

Finally, the synthesis specifies the framework's feedback boundary. Feedback mechanisms operate only as performance-to-governance learning loops, whereby observed deviations in productivity, schedule, cost, or safety inform managerial adjustment. Feedback does not flow to the hazard layer, and the hazard layer contains no internal adaptive dynamics. This boundary condition is crucial for ensuring that the framework remains a decision-oriented construction management model rather than an attempt to simulate hazard propagation.

Collectively, these constructs and boundary conditions convert the empirical evidence base into a coherent conceptual architecture that is both analytically explicit and managerially interpretable. They provide the theoretical basis for the governance-led, performance-centered framework presented in Section 4.

Table 1. Source-to-Concept Synthesis Table

Reference	Empirical Contribution	Conceptual Mapping in Framework
Han et al. (2025)	Meta-analysis of heat exposure and productivity loss	Climate stress → Performance degradation
Liu et al. (2024)	Seismic risk assessment and damage analysis	Seismic hazard → Vulnerability → Schedule/cost risk
Al-Asadi & Alrebeh (2024)	Seismic resilience metrics for structural performance	Seismic impact → Functional recovery trajectory
Oğuz & Hansu (2025b)	Post-event vulnerabilities and retrofitting emphasis	Disaster/seismic disruption → Recovery constraints
Seidu et al. (2025)	Climate resilience implementation model	Climate risk → Adaptive scheduling strategies

Rao et al. (2025)	Circular economy in construction review	Circularity → Cost stability, material resilience
Çetin & Kirchherr (2025)	Circular strategies for post-disaster reconstruction	Circularity → Recovery efficiency
Boje et al. (2020)	Digital twin and BIM-based monitoring in construction	Digital tools → Monitoring and feedback support
Kendirci et al. (2025)	Digital governance in climate-resilient systems	Digital enablement → Governance augmentation

4. Proposed Multi-Hazard and Climate-Resilient Construction Management Framework

4.1 Framework overview

This study proposes a Multi-Hazard and Climate-Resilient Construction Management Framework designed to support performance-oriented decision-making under compound risk conditions. Grounded in systems engineering logic, the framework conceptualizes construction projects as adaptive socio-technical systems in which external hazards impose stress, governance decisions provide control, and circular and digital systems act as enablers of adaptive capacity (Odebode, 2023).

Unlike traditional approaches that address climate adaptation, disaster resilience, and sustainability in isolation, the framework centers construction project performance as the organizing principle through which these domains are integrated. Performance is treated not merely as an outcome of design adequacy but as a dynamic system state shaped by hazard exposure, managerial intervention, and enabling support mechanisms. Accordingly, the framework is structured into four functional layers, each with a distinct role and explicitly defined directional relationships, as illustrated in Figure 2.

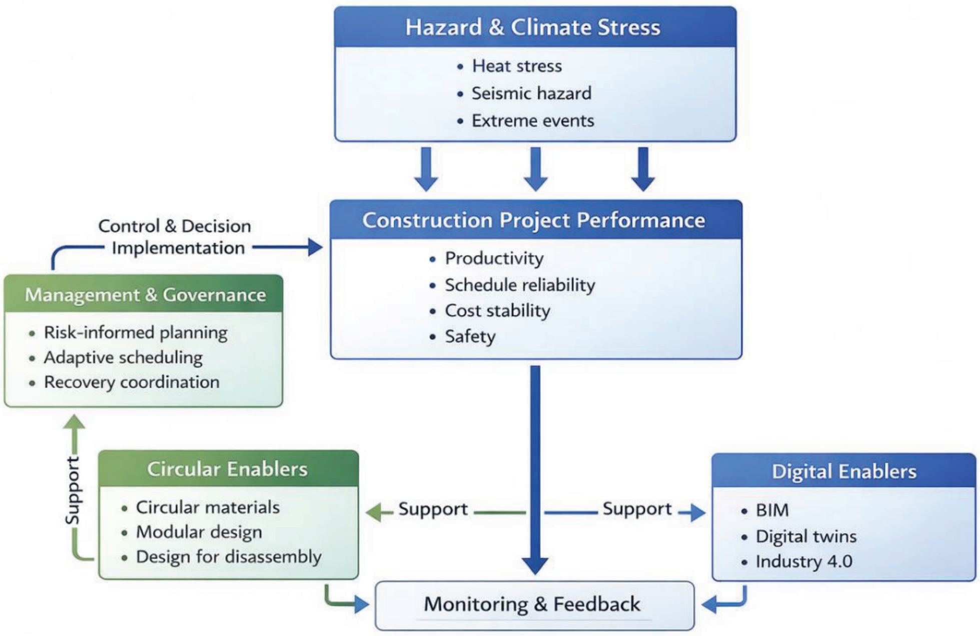

Figure 2. Multi-Hazard and Climate-Resilient Construction Management Framework

Within this framework, hazards are treated as exogenous forcing conditions, while management and governance constitute the sole decision-making and control authority over project performance. The Hazard and Climate Stress Layer represents external conditions acting upon construction systems, including chronic stressors such as heat exposure and episodic shocks such as earthquakes and flooding. These hazards influence performance through distinct but potentially compounding pathways; however, consistent with risk theory, they do not respond to system feedback or managerial intervention. Heat exposure, for example, reduces labor capacity and increases safety risk in a threshold-like manner, producing measurable productivity and scheduling impacts (Han et al., 2025). Seismic hazards and extreme events can generate abrupt damage, work stoppages, and recovery delays, with downstream consequences for schedule reliability and cost stability (Liu et al., 2024).

At the center of the framework, the Project Performance Layer defines the core outcomes to be stabilized and protected under multi-hazard exposure. Performance is operationalized through four dimensions—productivity, schedule reliability, cost stability, and safety—capturing both operational efficiency and resilience capacity. By framing resilience in terms of performance continuity and recoverability rather than hazard resistance alone, the framework aligns with recent construction resilience research emphasizing functional adaptation and continuity of operations (Li et al., 2024).

Beneath performance, the Management and Governance Layer functions as the exclusive locus of control and decision-making. Through risk-informed planning, adaptive scheduling, and post-disaster coordination, this layer translates hazard intelligence and performance feedback into operational strategies. Governance is deliberately isolated from material and digital systems to avoid conflating enabling capability with decision authority; performance change occurs only along the governance–performance control pathway.

Supporting governance are the Circular and Digital Enablers, which enhance system adaptability without exerting direct control over performance. Circular enablers—including modular construction, material reuse, and design-for-disassembly—strengthen physical recoverability, reduce reliance on disrupted supply chains, and improve lifecycle flexibility (Çetin & Kirchherr, 2025; Rao et al., 2025). Digital enablers—such as BIM, digital twins, and sensor-enabled analytics—augment situational awareness and predictive capacity by supporting monitoring, visualization, and scenario analysis (Seidu et al., 2025). Directional relationships within the framework flow from hazards to performance, from governance to performance through control actions, and from performance back to governance through monitoring and feedback, with no feedback pathways directed toward the hazard layer. The functional roles of each layer are summarized in Table 2.

Table 2. Functional Layers of the Multi-Hazard Construction Management Framework

Layer	Functional Role	Example Concepts
Hazard and Climate Stress	Exogenous risk exposure	Heatwaves, seismic shocks, flash flooding
Project Performance	Central performance outcomes	Productivity, schedule reliability, cost stability, safety
Management and Governance	Decision-making and operational control	Risk-informed planning, adaptive scheduling, recovery coordination
Circular and Digital Enablers	Performance support via adaptation enablers	Modular design, material reuse, DfD, BIM, digital twins, IoT analytics

4.2 Operational Logic of the Framework

The framework is operationalized through a structured management logic that translates the layered architecture into decision-oriented procedures applicable across construction contexts. This logic clarifies how governance actors respond to external hazard conditions, assess performance vulnerability, and deploy enabling systems to support adaptive decision-making, while preserving clear boundaries between control (governance), support (enablers), and feedback (monitoring).

The process begins with the identification of dominant hazard profiles relevant to the project's location, duration, and construction typology. Governance actors assess both chronic stressors (e.g., sustained heat exposure) and episodic hazards (e.g., seismic or hydrological events). At this stage, hazards are treated strictly as exogenous conditions that impose stress on the system but remain unaffected by managerial intervention or performance outcomes.

The second step involves the assessment of performance exposure, translating hazard information into performance-relevant terms across productivity, schedule reliability, cost stability, and safety. This step enables managers to identify which performance dimensions are most vulnerable and where degradation may occur, supporting prioritization of targeted interventions. The intent is not to replace probabilistic hazard modeling, but to ensure hazards are assessed through the lens of project performance stability.

Third, the Management and Governance Layer selects adaptive control strategies. These strategies may include adjustments to work sequencing, labor allocation, resource planning, safety management, and recovery preparedness. Decision authority remains exclusively within governance, ensuring that performance modification occurs only through managerial action rather than through autonomous technological or material responses (Galjanić et al., 2022). This step constitutes the primary control pathway linking governance decisions to project performance outcomes.

Fourth, circular and digital enablers are integrated in a supporting role. Circular systems support governance strategies by enhancing physical adaptability and recoverability, particularly under disruption, while reducing supply-chain dependency. Digital systems support situational awareness, predictive assessment, and scenario evaluation through information integration and monitoring. These enabling systems do not initiate decisions or alter performance independently; instead, they strengthen governance capacity to implement and refine selected strategies.

Finally, the framework relies on performance monitoring and feedback to enable iterative learning and adaptive management. Project outcomes are monitored through reporting systems and digital monitoring tools, generating performance information that flows back to governance actors (Boje et al., 2020). This feedback supports recalibration of strategies when performance deviates from acceptable thresholds. Crucially, feedback pathways are directed solely toward governance and do not extend to the hazard layer, preserving the conceptual distinction between external risk exposure and internal system adaptation.

Overall, this operational logic reinforces the governance-led and performance-centered structure of the framework. Resilience emerges through iterative managerial decision-making informed by monitoring feedback and supported by circular and digital enablers, rather than through hazard avoidance or technological determinism.

5. Managerial Decision Pathways and Practical Application

5.1 Hazard Performance Management Enabler Matrix

To translate the conceptual architecture of the Multi-Hazard and Climate-Resilient Construction Management Framework into actionable managerial guidance, this section introduces a Hazard–Performance–Management–Enabler Matrix (Table 3). The matrix operationalizes the layered logic developed in Section 4 by explicitly linking exogenous hazard conditions to their performance implications, corresponding governance-led management strategies, and supporting circular or digital enablers. In doing so, it provides a structured pathway for applying the framework's decision logic at the project level without introducing prescriptive or context-specific solutions.

The matrix reflects the core premise of the framework: hazards affect construction projects through identifiable performance degradation pathways; governance actors retain full decision authority in selecting adaptive responses; and circular and digital systems function as enabling supports rather than autonomous drivers of action (Opara et al., 2025). Each row therefore represents a coherent decision sequence—from hazard exposure, through performance impact, to managerial intervention and enabling support—consistent with the directional relationships defined in Figure 2. The structure allows for flexibility across project scales, institutional capacities, and technological contexts, including settings where advanced digitalization or modular systems may be limited.

Table 3 is not intended to function as a checklist or standardized risk register. Instead, it illustrates how the same framework logic can accommodate diverse hazard profiles and operational conditions by adapting management strategies and enablers to context-specific constraints. This approach reinforces the framework's emphasis on governance-led adaptation and performance stabilization under compound risk conditions.

Table 3. Hazard Performance Management Enabler Matrix

Hazard Type	Performance Impact	Management Strategy	Circular / Digital Enabler
Heat stress	Productivity loss, safety risk	Adaptive scheduling, task resequencing, shaded work zones	BIM-based planning, thermal exposure dashboards
Earthquake	Structural damage, workflow interruption	Seismic staging, retrofitting, emergency coordination	Modular systems, Design-for-Disassembly (DfD)
Flooding	Access delays, material loss, site shutdowns	Site drainage, logistics rerouting, equipment elevation	Digital twins, flood-zone mapping, mobile monitoring
Post-disaster conditions	Recovery delays, cost instability	Procurement flexibility, inspection acceleration, triage	Material recovery hubs, circular supply networks
Compound events (e.g., heat + seismic)	Crew fatigue + structural vulnerability	Phased work planning, contingency buffers, risk overlays	Predictive analytics, hybrid scheduling simulations
Climate-vulnerable regions	Systemic underperformance, long-term delays	Low-tech resilience planning, governance strengthening	Paper-based workflows, modular shelter kits, SMS alerts

The matrix demonstrates how different hazard types—thermal stress, seismic shocks, hydrological extremes, or chronic climate exposure—translate into distinct performance challenges that require differentiated governance responses. Importantly, the logic of control always flows from management and governance toward performance outcomes, while circular and digital systems provide context-appropriate support. As project conditions evolve, performance feedback enables governance actors to recalibrate strategies, maintaining operational resilience even under compound and dynamic hazard exposure (Lu & Yu, 2025).

5.2 Application contexts

The application of the proposed framework is inherently context-flexible, allowing its governance-led, performance-centered logic to be adapted across construction environments characterized by different hazard profiles, institutional capacities, and levels of technological maturity. Rather than introducing new mechanisms, the following application contexts demonstrate how the same decision pathways articulated in Section 4 and operationalized in Table 3 can be configured to support adaptive management under varying real-world constraints.

In urban mega-projects, construction activities are typically exposed to chronic heat stress, extreme weather events, and cascading logistical disruptions arising from dense urban settings. Governance challenges in these projects include complex contractual hierarchies, congested work zones, and fragmented risk coordination among multiple stakeholders (Zhang et al., 2024). Within this context, the framework supports proactive performance control by enabling governance actors to translate hazard exposure into targeted interventions focused on productivity stabilization, schedule reliability, and safety assurance. Digital enablers such as BIM and digital twins support real-time performance monitoring and scenario evaluation, while circular strategies—including modular construction and design-for-disassembly—reduce on-site complexity and facilitate adaptive resequencing when disruption occurs. Importantly, these enablers function strictly as decision-support mechanisms, reinforcing governance authority rather than substituting it.

In post-disaster recovery projects, construction systems operate under acute disruption, often characterized by aftershocks, damaged infrastructure networks, constrained supply chains, and intense time pressure. Governance challenges in this context include accelerated decision timelines, unclear institutional mandates, and bottlenecks in inspection or procurement processes (Chester et al., 2021). The framework guides recovery governance by prioritizing performance continuity and recovery speed through flexible planning and coordination mechanisms. Circular systems—such as material recovery, reusable components, and modular reconstruction—support rapid recovery by reducing dependency on external supply chains, while digital tools assist in damage assessment, progress tracking, and reprioritization. Crucially, the framework does not prescribe automation-driven recovery; instead, it emphasizes governance-led adaptation informed by evolving performance feedback.

In climate-vulnerable and resource-limited regions, construction projects face persistent exposure to heat stress, flooding, and infrastructure fragility, often compounded by limited institutional capacity and restricted access to advanced technologies. In such settings, the framework remains applicable by emphasizing governance awareness, performance prioritization, and context-appropriate enabling support rather than high-cost technological solutions (Amekudzi-Kennedy et al., 2024). Low-tech circular strategies—such as reusable local materials, simplified modular systems, and adaptive work sequencing—enhance resilience by reducing reliance on external inputs. Digital support may take the form of basic tools, including mobile-based reporting, SMS alerts, or simplified dashboards, rather than full-scale BIM platforms. Through governance-led decision-making supported by feasible enablers, the framework enables performance stabilization even under chronic exposure and resource constraints.

Across these contexts, the framework demonstrates its capacity to support adaptive, risk-informed construction management without reliance on uniform technological intensity or prescriptive solutions. By maintaining consistent control logic—where governance directs performance adaptation and enablers provide scalable support—the framework accommodates diverse operational realities while preserving theoretical coherence. This adaptability reinforces its relevance for both advanced construction systems and contexts where resilience must be achieved through pragmatic, low-cost interventions.

6. Limitations and Implementation Barriers

While the Multi-Hazard and Climate-Resilient Construction Management Framework provides a structured foundation for performance-based risk governance, several limitations and practical implementation barriers must be acknowledged to ensure accurate interpretation and guide future refinement. These limitations relate primarily to the current scope and implementability of the framework, while broader research directions are discussed separately in Section 8.

First, the framework is conceptual in nature and has not yet been validated through empirical case studies, simulation modeling, or quantitative performance benchmarking. Although its logic is grounded in a structured synthesis of empirically established research across multiple domains, its application under live multi-hazard conditions remains untested. Future validation using system dynamics modeling, agent-based simulation, or longitudinal project performance data would be required to examine the causal pathways and feedback assumptions embedded in the framework.

Second, the framework incorporates digital enablers such as BIM, digital twins, and real-time monitoring systems, yet the availability and maturity of these technologies remain uneven across the global construction sector. Effective implementation depends on digital infrastructure, workforce capability, data interoperability, and institutional readiness (Wadi et al., 2023). In many low- and middle-income contexts, these prerequisites may be absent or only partially developed, necessitating simplified or alternative forms of digital support aligned with local capacity.

Third, the framework assumes that governance functions—including risk-informed planning, adaptive scheduling, and post-disaster coordination—can be executed with a minimum level of institutional coherence. In practice, governance fragmentation, overlapping mandates, and inter-agency conflict are common, particularly in post-disaster and large-scale infrastructure contexts (Huck et al., 2020). Such governance failures may delay decision implementation, weaken accountability, or constrain adaptive responses, even when hazard information and enabling tools are available.

Fourth, the integration of circular construction strategies within the framework may face adoption barriers, especially in resource-constrained environments. These barriers include limited access to modular systems, absence of standardized material recovery protocols, regulatory inertia, and insufficient market incentives for circular supply chains. While circularity offers significant resilience and recovery benefits, its scalability remains contingent on broader institutional, regulatory, and market reforms beyond the project level.

Finally, although the concept of compound risk informs the layered architecture of the framework, it is not designed to simulate cascading multi-event sequences or dynamic inter-hazard feedback mechanisms, such as earthquake-triggered landslides or flood-induced structural failure chains. As a result, second-order and higher-order hazard interactions may be underrepresented in scenarios where one hazard amplifies the impact or timing of another.

Despite these limitations, the framework constitutes a robust theoretical contribution by clarifying the roles of hazard exposure, governance control, and enabling systems within a unified, performance-centered structure. Explicit recognition of these implementation barriers strengthens the framework's applicability by providing a transparent basis for future empirical validation, tool development, and institutional adaptation across diverse construction environments.

7. Discussion

7.1 Theoretical Contributions

This study advances construction management theory by moving beyond the dominant single-hazard and domain-specific models that have characterized much of the existing literature. Prior research has typically examined climate stress, seismic risk, disaster recovery, and sustainability as separate analytical problems, resulting in conceptual silos that limit explanatory power under real-world conditions where hazards co-occur and interact (Ward et al., 2022). Unlike these approaches, the present study advances a multi-hazard, performance-oriented systems perspective, in which construction projects are conceptualized as adaptive socio-technical systems exposed to simultaneous external pressures.

A key theoretical contribution lies in reframing construction project performance as the central analytical interface between hazard exposure and managerial intervention. Existing climate-focused studies have demonstrated that heat stress induces nonlinear productivity losses and heightened safety risks, yet these effects are rarely embedded within broader project control or decision-making theories. Similarly, seismic and disaster risk research has predominantly emphasized structural vulnerability and post-event recovery, with limited attention to construction-phase operational continuity. By integrating these strands, the proposed framework extends prior resilience research by shifting the analytical focus from hazard resistance to performance continuity, recoverability, and adaptive capacity (Liu et al., 2024). This perspective aligns construction management theory more closely with contemporary systems-based resilience thinking.

The framework further contributes by explicitly clarifying governance as the sole locus of decision-making and control within construction systems. In contrast to strands of digital construction and resilience literature that implicitly distribute agency across technologies, routines, and material systems, this study reinforces the primacy of managerial and institutional decision-making. Extending earlier findings by the authors on comparative construction risk governance and regulatory capacity, the framework isolates governance as the only layer capable of directly influencing performance outcomes (Hansu & Oğuz, 2025). In doing so, it strengthens theoretical accounts of construction management that emphasize human agency, institutional coordination, and adaptive planning under uncertainty.

Another important theoretical advance concerns the integration of circular construction principles into performance management theory. Much of the circular economy literature in construction has focused on environmental efficiency, material reuse, and lifecycle emissions, often decoupled from risk and resilience considerations. Building on the authors' prior work on modular and disassemblable construction systems, this study extends circularity theory by explicitly positioning circular strategies as resilience-enabling mechanisms that enhance recoverability, reduce supply-chain dependency, and stabilize costs during disruption (Oğuz & Hansu, 2025a). This integration bridges sustainability and resilience literatures that have historically evolved in parallel rather than in dialogue.

Finally, the framework contributes to digital construction theory by repositioning digital technologies as decision-support enablers rather than autonomous control systems. While prior studies have highlighted the potential of BIM, digital twins, and Industry 4.0 analytics for risk anticipation and coordination, they often imply a degree of techno-determinism. Extending the authors' earlier empirical findings, which demonstrated that digital tools enhance construction resilience only when embedded within robust governance structures, the present framework routes digital capabilities through monitoring and feedback mechanisms that inform—but do not replace—managerial judgment (Kendirci et al., 2025). Collectively, these contributions advance a more integrated, realistic, and theoretically robust understanding of resilience in construction management.

7.2 Practical and Policy Implications

Beyond its theoretical contributions, the proposed framework offers significant practical and policy implications for construction systems operating under accelerating climate and disaster pressures. Its decision-oriented structure provides construction managers with a clear logic for translating hazard exposure into adaptive strategies without relying on prescriptive or one-size-fits-all solutions. By linking hazards to measurable performance impacts, the framework enables project teams to prioritize interventions based on productivity loss, schedule disruption, cost escalation, and safety risk rather than abstract risk scores alone.

From a regulatory and policy perspective, the framework supports the development of climate-informed construction governance. Current regulatory approaches often emphasize design-stage compliance, with limited consideration of construction-phase performance under climate stress (von Malmborg et al., 2024). By explicitly connecting heat exposure and extreme events to operational outcomes, the framework provides a defensible basis for adaptive scheduling requirements, climate-responsive labor regulations, and performance-based construction standards. Such measures are increasingly necessary as climate stress becomes a persistent rather than exceptional condition.

The framework also has direct implications for post-disaster reconstruction governance. Empirical evidence consistently indicates that recovery delays and cost overruns are driven not only by physical damage but also by coordination failures and regulatory rigidity (Liu et al., 2024). By positioning post-disaster coordination as a core governance function supported by circular and digital enablers, the framework highlights the importance of institutional capacity, procurement flexibility, and information integration in accelerating recovery. Circular strategies such as material recovery and modular rebuilding reduce dependency on disrupted supply chains, while digital tools support damage assessment and coordination without displacing managerial authority.

In climate-vulnerable regions where institutional capacity and technological resources may be uneven, the framework offers a scalable and context-sensitive approach to resilience. Its emphasis on governance-led adaptation ensures that resilience does not depend solely on advanced digitalization but can be achieved through incremental improvements in planning, scheduling, and coordination. This aligns with earlier findings by the authors on smart city risk management, which emphasized that technology enhances resilience only when matched with appropriate governance structures (Kendirci et al., 2025).

Overall, the framework provides a structured basis for resilient and low-carbon project delivery by aligning climate adaptation, disaster risk reduction, and sustainability objectives within a unified performance-governance logic. These practical and policy implications reinforce the framework’s relevance for both industry practitioners and public decision-makers navigating the increasing complexity of contemporary construction environments.

8. Future Research Directions

While the proposed framework establishes a consolidated theoretical basis for managing construction projects under compound climate and disaster risks, its advancement into applied research requires targeted empirical and methodological development. Future studies should prioritize quantitative validation, digital integration, and longitudinal analysis to test and refine the framework's causal logic under real-world conditions.

A primary direction for future research is the quantitative validation of the framework's relationships among hazards, performance, governance, and enabling systems. As this study is intentionally theory-building, future work should employ methods such as structural equation modeling (SEM) to test hypothesized causal pathways between hazard exposure and performance outcomes, using measurable indicators including productivity loss, schedule deviation, cost variance, and safety incident rates. SEM would be particularly useful for examining mediation effects, such as how governance quality moderates the relationship between hazard intensity and performance degradation.

In parallel, system dynamics and agent-based modeling offer complementary approaches for exploring the temporal and behavioral dimensions of multi-hazard construction systems. System dynamics models could be used to simulate feedback loops between performance monitoring and governance adaptation over time, capturing lag effects in decision-making and recovery. Agent-based models, by contrast, could represent heterogeneous actors—such as contractors, regulators, and workers—to examine how fragmented or decentralized governance structures influence adaptive responses, coordination efficiency, and recovery speed under compound hazard scenarios.

Another promising avenue involves the integration of the framework within real-time digital twin environments. Future research could operationalize performance thresholds within digital twins, linking sensor-derived indicators (e.g., temperature exposure, productivity rates, equipment downtime) to governance decision triggers. Such studies should explicitly examine how digital systems can support human decision-making—by providing early warning, scenario comparison, and performance visualization—without introducing autonomous control or undermining accountability.

Longitudinal and lifecycle-based research designs also represent a critical opportunity for extending the framework. Future studies should track project performance from early planning through construction delivery and post-disaster recovery, enabling assessment of how adaptive management strategies evolve over time. Metrics such as recovery duration, cumulative cost escalation, and post-event productivity rebound could be used to compare projects adopting multi-hazard governance frameworks with those relying on traditional single-risk approaches.

Finally, future research should examine the institutional and socio-economic conditions that shape framework implementation in climate-vulnerable and resource-constrained settings. Comparative cross-regional studies could investigate how variations in regulatory capacity, procurement systems, labor informality, and access to enabling technologies affect the feasibility and effectiveness of governance-led adaptation. Such work would support the development of context-sensitive extensions of the framework while preserving its core performance-centered logic.

By pursuing these research directions, subsequent studies can move beyond conceptual integration toward validated, operational models of construction system resilience. This progression is essential for translating the framework into evidence-based tools that support adaptive, equitable, and performance-driven construction management under accelerating global risk conditions.

9. Conclusions

Construction projects are increasingly delivered under conditions of compound risk, where climate stress, episodic disasters, and sustainability imperatives interact to destabilize performance. Despite this reality, prevailing construction management approaches remain fragmented, addressing these pressures through isolated technical or policy lenses. This study responds by proposing a Multi-Hazard and Climate-Resilient Construction Management Framework that integrates climate adaptation, disaster risk reduction, and circular construction within a unified, governance-led, performance-oriented structure.

The primary contribution of the framework lies in its explicit and unambiguous system logic. Construction project performance is positioned as the central outcome to be stabilized, governance is defined as the sole source of decision-making and control, hazards are treated as exogenous forcing conditions, and circular and digital systems are framed as enabling—rather than autonomous—supports. This clear separation of roles addresses a persistent conceptual weakness in existing resilience models, particularly those that conflate technological capability with managerial authority.

Through a structured conceptual synthesis, the study consolidates insights from climate risk analysis, seismic engineering, post-disaster governance, and circular economy research into a coherent theoretical architecture. In doing so, it reframes construction resilience as a function of adaptive management capacity supported by feedback and enabling systems, rather than as a product of hazard resistance or design redundancy alone. This shift advances construction management theory toward a systems-based understanding of performance continuity and recoverability under uncertainty.

As a theory-first contribution, the framework does not claim empirical validation but provides a rigorously structured foundation for future simulation, digital twin integration, and longitudinal performance assessment. It also offers policy-relevant clarity by identifying the institutional roles, governance mechanisms, and managerial levers required to operationalize resilience across diverse construction contexts, including both technologically advanced projects and resource-constrained environments.

Ultimately, this research enables a more integrated and actionable approach to construction risk governance, equipping scholars, policymakers, and practitioners with a common conceptual language for navigating increasingly complex hazard environments. By aligning hazard awareness, performance management, governance control, and enabling systems within a single framework, the study establishes a foundation upon which evidence-based, scalable, and context-sensitive construction resilience strategies can be developed and implemented.

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Chapter 2

CARBON-COST OPTIMIZATION IN POST-EARTHQUAKE RECONSTRUCTION PROCESSES IN TURKEY: POLICIES AND SCENARIO ANALYSIS

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1. Introduction

Post-disaster reconstruction processes represent one of the most resource-intensive phases within the built environment, characterized by urgent timelines, large-scale material consumption, and significant environmental impacts. While the primary objective of reconstruction is to restore housing and infrastructure rapidly, growing global awareness of climate change has emphasized the necessity of integrating sustainability principles into these processes. In particular, the construction sector's substantial contribution to global greenhouse gas emissions has made carbon management a critical concern in post-disaster rebuilding strategies (IPCC, 2022).

In recent years, carbon footprint reduction has increasingly been linked not only to environmental responsibility but also to economic performance. Carbon emissions generate both direct and indirect economic impacts through energy costs, material production, transportation, regulatory compliance, and long-term operational expenses. Consequently, reconstruction projects that fail to account for carbon-related costs risk creating economically inefficient and environmentally unsustainable outcomes. This has led to the emergence of **carbon–cost optimization** as a strategic approach that seeks to balance emission reduction targets with financial feasibility across the entire project lifecycle.

Carbon–cost optimization involves the integrated assessment of construction materials, energy systems, organization, and design strategies under predefined emission constraints and budgetary limitations. Rather than treating sustainability as an added cost, this approach reframes carbon reduction as a long-term economic opportunity supported by energy efficiency gains, incentive mechanisms, and lifecycle cost savings (ISO 14040; EN 15978). Especially in post-disaster contexts, where public resources are limited and social resilience is critical, optimizing this balance becomes even more essential.

Türkiye, as a country highly exposed to seismic risks, has experienced extensive reconstruction efforts following major earthquakes. These reconstruction activities offer both challenges and opportunities: while rapid rebuilding is necessary, they also present a unique chance to integrate low-carbon technologies, energy-efficient materials, and sustainable policy instruments into the built environment. National climate commitments, including long-term emission reduction targets, further necessitate the alignment of reconstruction practices with carbon management strategies (Liu et al 2022).

Within this context, this chapter aims to examine carbon–cost optimization in post-disaster reconstruction processes through a structured analytical framework. The study focuses on carbon footprint measurement methodologies, scenario-based carbon–cost analysis, policy integration, financial incentive mechanisms, and standardization approach relevant to Türkiye. By combining environmental and economic perspectives, the chapter seeks to provide decision-makers, planners, and researchers with a comprehensive toolset for developing reconstruction strategies that are both cost-effective and climate-resilient.

2. Measurement of Carbon Footprint in Reconstruction Processes

The measurement of carbon footprints in reconstruction processes plays a critical role in achieving effective and sustainable development objectives following disaster events. This process enables the quantitative assessment of greenhouse gas emissions across all stages of reconstruction activities, thereby establishing a fundamental database for recording, monitoring, and reducing carbon emissions.

During the assessment phase, construction materials, energy consumption, transportation and logistics activities, and resource use throughout construction processes are analyzed in detail. These analyses are essential for distinguishing between direct and indirect emission sources and for identifying potential mitigation measures at each stage. Carbon footprint measurement also serves as a guiding tool for enhancing sustainability and cost efficiency in reconstruction projects. By adopting sustainable material alternatives, applying energy-efficient techniques, and optimizing waste management practices, environmental impacts can be significantly reduced.

When integrated with reconstruction customization and cost assessment approaches, carbon footprint measurement supports the development of targeted emission reduction strategies and long-term sustainability objectives. These processes contribute not only to environmental resilience but also to economic and social sustainability by promoting construction solutions that enhance overall quality of life and structural durability.

4. **Scenario Analysis Methodology**

Scenario analysis methodology aims to systematically evaluate alternative future pathways and uncertainties to achieve effective carbon–cost optimization in reconstruction processes. This approach involves defining a set of assumptions and variable parameters, followed by the simulation of their potential impacts. Key factors considered include climate policies, technological advancements, cost trends, regulatory changes, and macroeconomic conditions.

By constructing multiple scenarios, the multidimensional relationship between carbon footprint and costs can be examined in depth. This enables the identification of integrated solutions that are most suitable for both policy formulation and implementation. Scenario analysis contributes to the development of sustainable reconstruction strategies and ensures long-term cost efficiency while offering flexible and adaptive planning options to address future uncertainties. Consequently, this methodological framework supports both the evaluation of current conditions and the anticipation of future developments, providing decision-makers with a comprehensive foundation for strategic planning.

4.1. Life Cycle Carbon Assessment (LCA)

The analysis is based on the EN 15978 standard. The following life cycle stages are included:

A1–A3: Material production (cement, steel, aggregates, and logistics)

A4–A5: Transportation to site and construction processes

B: Use phase (based on thermal performance assumptions)

C: Demolition and end-of-life treatment

Based on the existing literature, it is assumed that the largest share of carbon emissions in post-disaster reconstruction projects occurs during the A1–A3 stages (Pomponi & Moncaster, 2018).

4.2. Life Cycle Cost Analysis (LCC)

- Initial investment costs (CAPEX)
- Operational costs
- Maintenance and repair costs
- Impact of future carbon pricing mechanisms (including ETS integration) on total costs
- A 5% discount rate is applied in the analysis.

5. Existing Policy Framework in Türkiye

Türkiye's existing policy framework incorporates various instruments and structural mechanisms that support carbon–cost optimization in reconstruction processes. Policy integration at both national and local levels aims to align sustainability objectives with reconstruction efforts for buildings and infrastructure. Regulations promoting energy efficiency and environmental sustainability, along with emission reduction obligations and incentive schemes, form the core of this framework.

Financial incentives and cost assessment approaches, particularly in post-disaster reconstruction projects, aim to deliver cost-effective solutions. Government supports mechanisms, tax incentives, and credit facilities that enable private sector actors and local authorities to develop projects aligned with sustainable construction principles. Additionally, standards, codes, and performance criteria are continuously updated to limit carbon emissions and improve building energy performance.

The integration of carbon footprint and cost analyses within the policy framework enables reconstruction projects to generate more sustainable solutions by balancing carbon–cost trade-offs. These approaches allow construction processes to be optimized in ways that minimize environmental impacts while accounting for post-disaster time constraints and infrastructure demands. Overall, Türkiye's policy environment provides a suitable foundation for carbon–cost optimization strategies, with a strong focus on renewable energy integration, energy efficiency, and sustainable material use.

5.1. National and Local Policy Integration

National and local policy integration is critical to the successful implementation of carbon–cost optimization in reconstruction processes. This integration ensures coordination and coherence across different governance levels, facilitating sustainable and efficient practices. Alignment between national climate and sustainability targets and local needs and conditions is essential. National energy, construction, and transportation policies should therefore serve as reference points for local planning and implementation processes.

Strengthening communication and information exchange among institutions and stakeholders is a key component of effective policy integration. This enables the development of carbon reduction measures and cost-efficient strategies. Furthermore, the widespread adoption of sustainable construction standards and building codes enhances consistency and quality in implementation. Ensuring compliance with internationally recognized norms in data collection and reporting improves the accuracy and reliability of carbon–cost analyses.

At the local level, tailored incentive mechanisms and cost advantages aligned with regional needs can increase social acceptance and accelerate implementation. Policy environments that support the integration of local sustainability and carbon management strategies are therefore essential. Addressing inconsistencies between national and local policies and enhancing interdepartmental coordination further ensures that reconstruction projects are environmentally and economically sustainable while remaining adaptable to local conditions.

5.2. Financial Incentives and Cost Assessment Approaches

Financial incentives and cost assessment approaches are among the most effective tools for promoting sustainability in reconstruction processes. Government incentives, tax reductions, low-interest loans, and direct financial support encourage investments aimed at reducing carbon footprints in the construction sector. These measures facilitate the adoption of energy-efficient technologies and sustainable materials while reducing overall costs.

Carbon pricing mechanisms further reflect the true economic cost of emissions, prompting investors and practitioners to internalize carbon impacts in decision-making. Carbon credit and emissions trading systems aim to optimize costs while transforming carbon reduction into an economic imperative. Cost assessment approaches involve detailed calculations of additional costs and potential savings associated with reconstruction projects.

Lifecycle costing methodologies play a critical role by analyzing carbon and cost data holistically from project inception to completion. This enables the identification of optimal solutions under different scenarios, supporting both sustainability goals and economically rational decision-making. Transparency and accountability in the design and implementation of financial incentives are essential to ensure their effectiveness and long-term viability. Overall, the integrated planning of policy instruments and financial tools enables effective carbon–cost optimization and supports the development of cost-efficient reconstruction processes aligned with long-term climate objectives.

5.3. Standards, Codes, and Implementation Performance

Standards, codes, and implementation performance play a decisive role in carbon–cost optimization within reconstruction processes. These elements form the foundation of sustainable and efficient reconstruction practices. National and international construction standards establish key criteria related to structural resilience, energy efficiency, and environmental impact. In Türkiye, updating and enforcing post-disaster reconstruction standards is particularly important for reducing risks and minimizing carbon footprints.

Technological advancements and innovations should be incorporated into code implementation, and performance should be continuously monitored to enable corrective actions when necessary. Performance-based criteria and certification systems support quality assurance and sustainability expectations within the construction sector. The practical effectiveness of standards directly influences both carbon emissions and project costs.

In addition to structural durability and energy efficiency, material selection should prioritize environmentally friendly and cost-effective solutions compliant with relevant standards. Strengthening control mechanisms, standardizing inspection, and reporting processes, and enhancing monitoring frameworks are essential for improving implementation performance. Regular updates and effective enforcement of standards and codes therefore represent a cornerstone of carbon–cost optimization, enabling controlled management of risks and costs while improving the environmental performance of the construction sector.

6. Scenario Design and Parameters

The scenario design and parameter identification phase involves developing multiple reconstruction pathways and policy alternatives. This process begins with defining transition scenarios that incorporate varying levels of energy integration, material usage ratios, and infrastructure renewal rates. Carbon–cost balances serve as the primary reference, with emission targets, economic sustainability, and infrastructure capacity acting as key constraints for comparative evaluation.

Post-disaster timelines and infrastructure demand further enhance the realism and feasibility of scenarios. Different policy assumptions and external parameters—such as economic conditions, technological developments, and regulatory updates—are systematically modeled and integrated into simulations. This approach enables the formulation of adaptive strategies suitable for a range of future conditions, providing decision-makers with a comprehensive comparative framework.

6.1. Transition Scenarios

Transition scenarios define flexible and diversified strategies that underpin carbon–cost optimization in reconstruction processes. These scenarios reflect alternative policy, and implementation approaches applicable to post-disaster infrastructure and construction activities.

The Low-Carbon Reconstruction Scenario prioritizes innovative materials, energy-efficient designs, and environmentally friendly technologies. Although initial costs may be higher, long-term savings through energy efficiency and emission reductions can offset these expenditures. The Carbon-Neutral Reconstruction Scenario aims to eliminate net emissions through comprehensive renewable energy integration and carbon offset mechanisms. Despite higher investment requirements and complex coordination, this approach represents a leading model aligned with long-term climate policies. Finally, the Integrated Scenario combines technological and financial strategies to optimize flexibility and adaptability. By blending different approaches, this scenario seeks to achieve effective and sustainable reconstruction outcomes tailored to local conditions.

6.2. Carbon–Cost Balances and Constraints

Carbon–cost balances and constraints are essential for maintaining equilibrium between sustainability objectives and economic feasibility in reconstruction processes. Emission limits and carbon pricing mechanisms directly influence total project costs, potentially increasing financial burdens while ensuring environmental compliance (D’Agostino, & D’Agostino, & 2021).

To optimize this balance, specific parameters and thresholds are defined, including criteria that limit carbon intensity in energy use and material selection, target emission levels, and cost-effectiveness requirements. Engineering design and construction planning incorporate flexibility through defined tolerances, enabling adaptation without compromising sustainability goals.

Exceeding established thresholds may lead to rapid cost escalation or deviations from sustainability targets. Therefore, clearly defined constraints and balanced parameterization are critical to ensuring that reconstruction projects remain both environmentally responsible and economically viable.

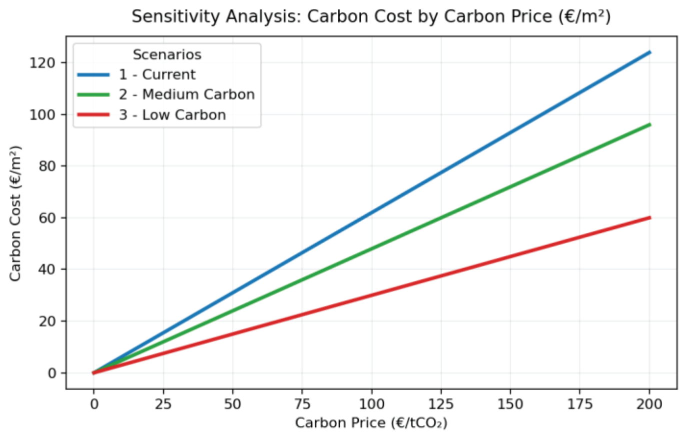

Figure 1. Sensitivity Analysis: Carbon Cost by Carbon Price (€/m²)

Linear carbon-cost intensities to match your Turkish plot's slopes (≈0.62, 0.48, 0.30 €/m² per €/tCO_2), so values at €200/tCO_2 are 124, 96, and 60 €/m², respectively. If you have exact intensities, send them and I will regenerate figure 1 precisely.

6.3. Post-Disaster Timelines and Infrastructure Loads

Carbon–cost balances are significantly shaped by the existing policy and regulatory environment. In Türkiye, long-term legislative frameworks define emission reduction targets, carbon pricing mechanisms, and energy efficiency requirements, while cost limits and constraints are structured accordingly. Legal obligations—particularly those related to energy performance and sustainability standards—serve as key instruments for limiting the carbon footprint of reconstruction projects. The definition and enforcement of clear constraints therefore enable a balanced alignment between economic efficiency and environmental objectives.

Post-disaster timeline planning plays a critical role in accelerating reconstruction processes while maintaining cost efficiency. These timelines determine the sequencing of project phases—ranging from damage assessment and excavation to infrastructure renewal and superstructure construction—and directly influence both infrastructure loads and carbon emissions. Optimized scheduling allows for more efficient resource allocation, reducing unnecessary energy consumption and material waste.

7. Strategies for Carbon–Cost Optimization

Achieving effective carbon–cost optimization requires the adoption of integrated strategies throughout all stages of reconstruction. At the design phase, carbon management plays a significant role. Priority should be given to energy-efficient technologies and low-carbon materials, along with sustainable design solutions that extend building lifespan and enhance operational performance. Selecting materials with low embodied carbon and reduced transportation requirements contributes simultaneously to cost reduction and emission mitigation.

During construction, efficiency and waste management are critical. Innovative construction methods and technologies that minimize energy use and material losses enable cost optimization while reducing environmental impacts. In addition, optimizing organization routes and transportation loads helps lower carbon emissions and total project costs. These measures not only improve sustainability performance but also shorten construction durations, thereby reducing financial and operational risks in post-disaster reconstruction projects.

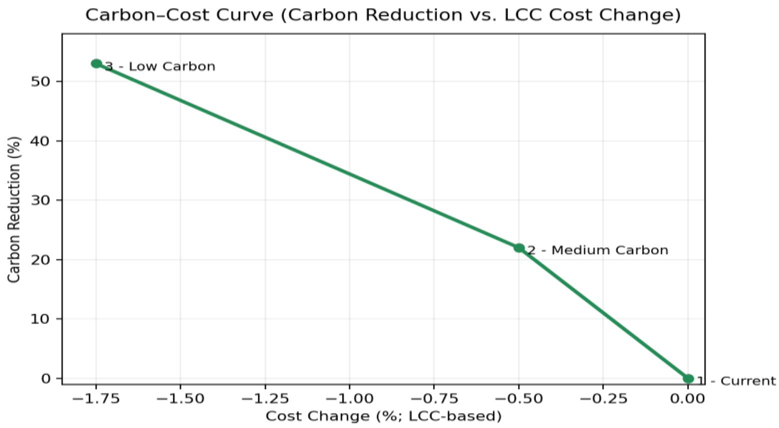

Figure 2 Carbon–Cost Curve (Carbon Reduction vs. LCC Cost Change) Sandanayake, (2018).

The Turkish graph's coordinates (Current: 0%, 0%; Medium: −0.5% cost, ~22% carbon; Low: −1.75% cost, ~53% carbon). have the exact values, send them and regenerate precisely (Figure 2).

8. Financial, Technical, and Policy Dimensions of Carbon–Cost Optimization

From a financial perspective, the development of revised cost structures and advanced financial models significantly enhances the sustainability of post-disaster reconstruction projects. The effective use of carbon pricing mechanisms and incentive schemes plays a key role in balancing costs while encouraging emission reductions. Innovative financing instruments and cost-sharing models further improve the economic attractiveness of reconstruction projects, facilitating the redirection of investments toward low-carbon and environmentally friendly Technologies Gursel & Ostertag, (2020)

Carbon Footprint Results

Table1. carbon calculations are based on literature-derived average coefficients (UNEP, 2023):

Scenario	Structural System	Material Source	Total Carbon (kg CO_2-eq/m²)
1	C30 Reinforced	Long distance (300 km)	**620**
2	Low-additive Concrete	Partially local (80 km)	**480**
3	Geopolymer	Fully local (30–50 km)	**290**

Result: The greatest reduction is observed in the combination of geopolymer and local production (53% decrease) (Table1).

Cost Results

Table 2 Cost-carbon designs

Scenario	**Construction Cost (₺/m²)**	**30-Year Operating Cost**	**Totals**	**Estimated Carbon Cost***
1	14.000	9.000	23.000	1.200
2	14.800	8.100	22.900	900
3	15.600	7.000	22.600	600

Although initial costs increase, low-carbon designs are more advantageous in terms of LCC overall (table 2).

(Note: Carbon price is projected to be in the range of €100–150/ton by 2030.)

Optimization Model Outputs

When LCC and carbon cost are considered together, Scenario 3 offers the most optimal solution.

Up to 30% carbon reduction can be achieved with only a small (<10%) increase in cost.

Construction site electrification reduces total carbon by 8–10%. Pomponi & Moncaster (2018).

The success of these strategies strongly depends on active support from public policies and regulatory institutions. Regulatory frameworks should be strengthened through financial incentives and policy instruments that promote low-carbon and cost-efficient reconstruction practices. Such integrated approaches form the foundation for harmonized implementations that simultaneously ensure economic sustainability and environmental responsibility.

Integrated carbon management at the design stage is a critical factor in achieving long-term sustainability goals. Optimizing material selection, construction technologies, and energy-efficient design principles reduces embodied and operational carbon emissions while maintaining cost efficiency. The integration of renewable energy systems and lifecycle-based scenario analyses during the design phase supports informed decision-making and improves both environmental and economic performance.

Material selection and transportation optimization also play a decisive role in reducing carbon footprints and controlling costs. Prioritizing low-carbon, durable, and locally sourced materials shortens transport distances and lowers emissions. Optimizing transport loads, organization planning, and adopting low-emission or electric transport solutions further enhances carbon–cost efficiency. Similarly, efficiency improvements and waste management in construction processes—through resource optimization, recycling, and energy-efficient technologies—reduce emissions while providing tangible cost advantages.

Re-costing and financial modeling serve as strategic tools in aligning carbon reduction targets with economic feasibility. Flexible and adaptive financial models that incorporate carbon pricing, return-on-investment periods, and risk analyses enable projects to respond effectively to changing market and policy conditions. However, implementation faces several challenges, including data quality limitations, market, and price volatility, and legal or regulatory barriers. Addressing these risks requires transparent data systems, adaptive planning approaches, and dynamic regulatory frameworks capable of accommodating technological and policy advancements.

9. Discussion and Policy Insights

Carbon–cost optimization in post-disaster reconstruction offers substantial opportunities for aligning sustainable development goals with climate policy objectives. Integrated carbon management, optimized material organization, and efficiency-driven construction practices significantly reduce emissions while enhancing cost performance. Financial incentives and supportive cost mechanisms encourage stakeholders to adopt innovative, low-carbon solutions. Nevertheless, overcoming challenges related to data reliability, market uncertainty, and regulatory rigidity remain essential. Future policies should prioritize flexible, scenario-based planning and integrated carbon–cost strategies to strengthen resilience and long-term sustainability.

10. Conclusion and Policy Recommendations

Carbon–cost optimization represents a critical instrument for achieving environmentally and economically sustainable post-disaster reconstruction. This study demonstrates that integrating holistic carbon management at the design stage, optimizing material selection and logistics, improving construction efficiency, and adopting adaptive financial models can significantly reduce both carbon emissions and lifecycle costs. Key barriers—such as data limitations, market volatility, and regulatory constraints—necessitate coordinated, flexible, and forward-looking policy responses.

When low-carbon binders, local sourcing, and construction-site electrification are implemented together, both carbon emissions and total lifecycle costs decrease substantially. Accordingly, the integration of LCA and LCC calculations into reconstruction standards is strongly recommended. Policies that promote local production, waste-based binders, tax incentives for electric construction equipment, and carbon scoring systems in public procurement—particularly in TOKİ-led and public tender projects—are identified as critical steps toward sustainable and cost-effective reconstruction practices.

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Chapter 3

REVIEW OF ELEVATOR IMPLEMENTATION PHASES IN CONSTRUCTION PROJECT MANAGEMENT WITHIN THE SCOPE OF THE LITERATURE

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1. Introduction

The regulations governing elevator applications in building construction are becoming increasingly diverse. The main reasons for this are the failure to comply with regulations regarding elevator installations, the inadequacy or ambiguity of regulatory provisions, and the lack of sufficiently deterrent sanctions.

In Türkiye, the following regulations are currently in effect concerning elevators: the Planned Areas Development Regulation, the Elevator Regulation (2014/33/EU), the Elevator Periodic Inspection Regulation, the Elevator Operation and Maintenance Regulation, the Elevator Market Surveillance and Inspection Regulation, and the Communiqué on Procedures and Principles Regarding the Design of Elevators (SGM:2017/18). However, despite these regulations, elevator accidents, unsafe elevators, and unregistered elevators are still observed. Situations that should not occur or should be rare according to regulations are frequently encountered. It is clear that unsuitable and unregistered elevators pose a potential risk of accidents.

Another important point is that elevator installations nationwide are divided into two parts: pre-registration and post-registration periodic inspections. Considering electric passenger elevators, the most frequently used type of elevator in Türkiye, the "Annex 05.B Inspection Criteria for Electrically Driven Elevators" is applied in both types of inspections. According to these criteria, elevators are evaluated in terms of 958 different sub-items. It is clear that inspections covering so many sub-items can negatively affect elevator installation processes.

No comprehensive study has been found that fully addresses both the relevant legislation and the problems encountered. Furthermore, while not entirely comprehensive, existing studies on the subject are generally few and insufficient. It has been determined that studies are limited to specific provinces, compared to previous legislation, examine non-conformities related to the initial periodic inspection before registration, and propose models for improving Ministry inspections using Elevator Tracking System (ASTAK) and Ministry of Industry and Technology inspection data. Another important issue is the lack of a study evaluating pre- and post-registration periodic inspections of elevators in building construction nationwide, examining the problems encountered, and identifying the source of these problems. Additionally, there is no guide outlining the situations that may arise from the beginning to the end of the elevator installation process, ensuring that parties are familiar with the process.

The primary aim of this study is to create a guide that clearly defines the procedures followed in accordance with the legislation regarding pre- and post-registration applications of registered elevators in Türkiye, and to examine the problems encountered as mentioned in previous studies. This study consists of six main sections: Introduction, Materials and Methods, Elevator Application Stages in Building Construction, Pre-Registration Initial Periodic Inspection Stage, Post-Registration Annual Periodic Inspection Stage, Previous Studies, Results, and Recommendations.

2. Materials and Methods

In Türkiye, the following regulations are currently in effect regarding elevators: “Planned Areas Zoning Regulation”, “Elevator Regulation (2014/33/EU)”, “Elevator Periodic Inspection Regulation”, “Elevator Operation and Maintenance Regulation”, “Elevator Market Surveillance and Inspection Regulation”, and “Communiqué on Procedures and Principles Regarding the Design of Elevators (SGM:2017/18)”.

According to the Elevator Periodic Inspection Regulation, for elevators put on the market for the first time, “pre-registration initial periodic inspection” and “annual periodic inspection” inspections are carried out to ensure the safe use of the elevator. Considering electric passenger elevators, the most frequently used type of elevator in Türkiye, “Annex 05.B Inspection Criteria for Electrically Driven Elevators” is used as the basis for both types of inspections. In this context, the first stage aims to create a guide that encompasses all of these regulations, providing a flowchart and a roadmap for elevator application in project management. In this study, a guide has been created by developing a flowchart for elevator application in project management within the scope of the legislation. In the second stage, the problems encountered are addressed using resources obtained from literature. These resources were obtained from Web of Science, Google Scholar, Scopus, and the Turkish Higher Education Council Thesis Database. In this study, publications related to elevator legislation and elevator applications in building construction were researched using the keywords "Elevator," "Construction Project Management," and "Elevator Periodic Inspection." The studies identified within the literature and the relevant legislation were evaluated together.

3. Steps and Guidelines for Elevator Installations

In our country, the application steps that must be completed for an elevator to be registered and put into service are presented as a guide in Figure 1.

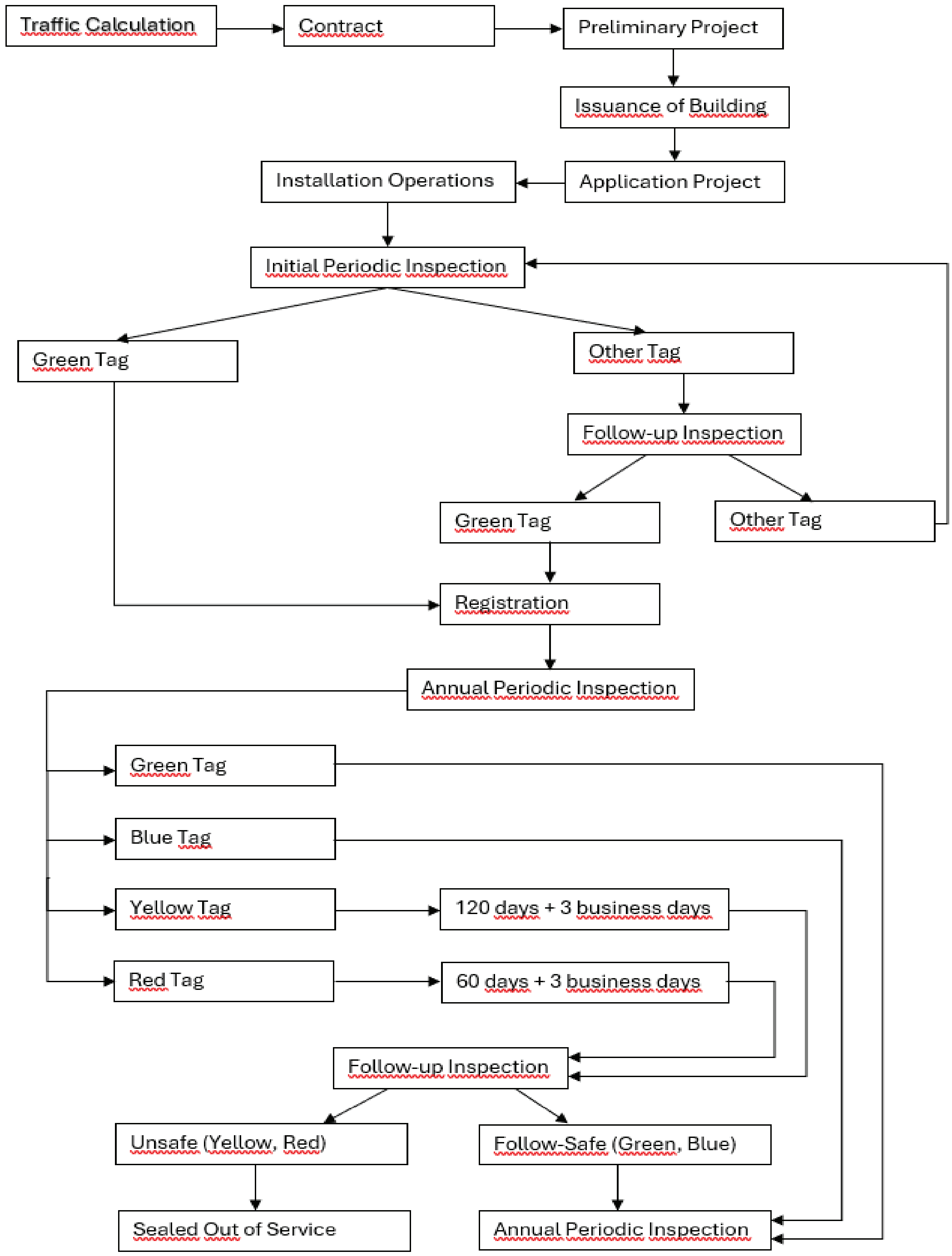

Figure 1. Guide to elevator installation stages in building construction.

4. Initial Periodic Inspection Stage Before Registration

In our country, elevator applications in building construction are regulated in accordance with the provisions of the "Planned Areas Zoning Regulation", "Elevator Regulation (2014/33/EU)", "Elevator Periodic Inspection Regulation", "Elevator Operation and Maintenance Regulation" and "Communiqué on Procedures and Principles Regarding the Design of Elevators (SGM:2017/18)". Article 34/1 of the Planned Areas Zoning Regulation states that "...in buildings with 3 floors, provision of elevator space is mandatory, and in buildings with 4 or more floors, elevator installation is mandatory." (Planned Areas Zoning Regulation, 2017). The Communiqué on Procedures and Principles Regarding the Design of Elevators addresses this in the following four stages:

1. Traffic Calculation
2. Contract
3. Preliminary Project
4. Implementation Project

In the first stage, the traffic calculation must be carried out by the elevator contractor in order to determine the number and specifications of the elevators. The traffic calculation includes the number of people who will use the elevator, the elevator capacity, the elevator speed, the travel time required for one trip, and the number of people to be transported in a specific time, all calculated according to the physical characteristics of the building (Notification Regarding the Procedures and Principles of Elevators, 2017).

In the second stage, after the traffic calculation is completed, an installation contract is signed between the elevator owner or building manager and the company that will install the elevator, specifying who will carry out the work and procedures related to the elevator design.

In the third stage, the preliminary elevator project includes the travel distance and speed, force calculations and motor power calculations, along with the building's zoning information, the standard according to which the elevator was designed, and the information obtained as a result of the traffic calculation. The preliminary elevator project, prepared by the company with which the elevator designer signed the installation contract, can be directly approved by the licensing authority or can be included in the annexes of the building permit without approval.

In the fourth stage, after the approval of the building permit, the implementation project is prepared by the company with which the elevator owner signed the installation contract and submitted to the licensing authority for approval. After this stage, it is the responsibility of the elevator installer to manufacture the elevator in accordance with the approved application project. In the next stage, the registration procedures for the elevators are carried out in accordance with the Elevator Operation and Maintenance Regulation. Finally, after the completion of the elevator installation, the first periodic inspection before registration must be carried out. The first periodic inspection before registration is carried out by Type A inspection organizations authorized by the Ministry of Industry and Technology. This inspection is carried out by an authorized Type A inspection organization that has signed a protocol with the administration where the building is located. The elevator, which receives a green information label as a result of the first periodic inspection before registration, is registered by the relevant administration as a result of the application made by the elevator installer with the documents specified in the Elevator Operation and Maintenance Regulation.

5. Annual Periodic Inspection Phase Performed After Registration

Elevators that have undergone their first periodic inspection before registration are required to undergo periodic inspections every year thereafter, regardless of whether they are registered or not. These inspections must be carried out upon the request of the building manager or ex officio by a Type A inspection organization with which a protocol has been signed by the relevant administration (Elevator Periodic Inspection Regulation, 2018). As a result of the annual periodic inspection, information labels of four different colors are attached to the elevators as defined below.

• An elevator with a green information label is flawless and poses no risk in its use.

• An elevator with a blue information label has minor defects. The defects, which do not negatively affect life and property safety, must be rectified before the next periodic inspection.

• An elevator with a yellow information label is defective, and the defects identified must be rectified before the follow-up inspection to be carried out within 120 days.

• An elevator with a red information label is unsafe, and the defects identified must be rectified before the follow-up inspection to be carried out within 60 days.

If elevators with yellow and red information labels are not brought to a safe or slightly defective (green or blue information label) condition, they will be sealed and taken out of service to prevent their use, based on a notification from a Type A inspection body.

6. Previous Studies

In this section, studies on the subject in literature are examined under two main headings: domestic and international.

6.1 Domestic studies

In the literature, there are numerous studies investigating the installation and regular maintenance processes of electric passenger elevators, and outlining national and international regulations related to these applications. Some of these sections are summarized below:

Demir's (2021) master's thesis entitled "Results of Periodic Inspections of Elevators in Çorum and New Generation Safety Measures in Elevators" investigated the most significant deficiencies and their causes by examining the periodic inspection reports of elevators installed in Çorum between 2017-2019. The study examined the changes introduced by the TS EN 81-20 standard and presented examples of the most frequent problems associated with the new standard. The study focused only on annual periodic inspection reports, and it was found that the inspection reports examined specifically for Çorum could be reviewed based on their main points, identifying the most frequent information. Furthermore, it has been concluded that training for employees working in the elevator sector, raising awareness among building managers and apartment owners, and implementing administrative procedures can be effective in preventing accidents in elevators.

In the master's thesis entitled "Comparison of TS EN 81-20 and TS EN 81-1/2 Standards in Passenger Elevators" by Aytaç (2018), the differences between the current standard used today and the standard mentioned are examined. The transition process details are classified, and solutions for reporting are developed. The continuous application of the improved technology of the TS EN 81-20 Standard in regular elevator inspections has resulted in positive outcomes in terms of occupational health and safety, as well as the safety of the elevator itself.

The systems thesis by Kaybal (2015), titled "Examination of Market Surveillance and Control and Periodic Inspection Processes in Elevators, Comparison with EU Practices and Proposal of Solutions Regarding Experiences in Practice," examines the national legislation commonly used and the legislation used by EU members, and draws conclusions based on calculations. In addition, it includes information on the shortcomings of continuous legislative regulations and sector practices. It can be concluded that these shortcomings can generally be corrected by: increasing the number of Market

Surveillance and Control options, regulating elevator regulations in national legislation concerning buildings, transferring the quality of services of rated actors, and centrally increasing the number of elevator users

The study titled "Elevator Market Surveillance and Inspection Process Improvement Model Proposal with Elevator Tracking System" by İspiroğlu (2021) focuses on the collection and effective processing of big data in the elevator sector, a problem solved by the Ministry. The study utilizes ASTAK data and the results of on-site inspections conducted by the Ministry. The study examines, on a provincial basis, how much the efficiency of inspections can be increased within the scope of the financial audit of the developed model, and it was determined that the new model can improve the efficiency of inspections. Furthermore, it was concluded that a new system, developed by bringing together data from all members in the elevator sector, could contribute more to inspection activities. The report titled "Elevator Market Surveillance and Inspection Practices and Future Perspectives" by Yazgan (2021) provides a general evaluation of existing PGD (Processed Elevator Market Surveillance and Inspection) processes related to elevators and offers solutions to these problems based on legislative provisions. The study evaluated the shortcomings in the effectiveness of all regulations and actors in the elevator industry and assessed what kinds of solutions could be implemented to reverse this trend.

The paper titled "Evaluation of Periodic Inspection Activities in Our Country" prepared by Demircan (2021) aims to evaluate the pre-registration initial periodic inspection criteria used in our country and to offer suggestions for improving these criteria used during inspections. The most frequently identified nonconformities resulting from the pre-registration initial periodic inspections carried out in 2021 were determined. Furthermore, improvement suggestions were made for the items in the checklist prepared in accordance with the TS EN 81-20 standard, and comparisons were also made with checklists used abroad. The study concludes that the initial periodic inspection criteria, which are of great importance in the construction and use process of buildings, should be separated from the annual periodic inspection criteria and reorganized.

In the master's thesis entitled "Results of Periodic Inspections of Elevators in Isparta and New Generation Safety Measures in Elevators" prepared by Tekin (2015), the reports of elevators that underwent periodic inspections in Isparta Province between 2013 and 2014 were examined to identify the most frequently encountered non-conformity criteria. Furthermore, by considering the new generation safety measures introduced by the TS EN 81-1+A3 standard, which came into force in 2012, it was concluded that the control criteria applied to elevators to be placed on the market reduce the likelihood of negative situations.

6.2 International Studies

The article “Extending the useful life of elevators through appropriate maintenance strategies” by Zhang and Zubair (2022) aimed to investigate whether the average useful life of elevators installed in buildings is 20-25 years and to find solutions on how to extend this lifespan. The study examined 25,548 different failure records from 5,400 different elevators in Hong Kong; the elevators were classified according to age groups and analyzed using data analysis. The analysis revealed that elevators experience more failures after an average of 30 years, and when the problems were examined using Pareto analysis, it was understood that the most significant problems stemmed from four different causes. These four problems were: controller, cabin door mechanism, floor door mechanism, and cabin interior failures. It was suggested that increasing risk-based maintenance could extend the elevator's useful lifespan by addressing these four major problems.

The article “The causal factors of elevator maintenance: a perspective from Saudi Arabia healthcare facility management” by Alassafi, Al-Gahtani, Almohsen, and Alfalah (2022) aimed to identify and prevent potential problems related to the use and cost of elevators within the Saudi Arabian healthcare system. The study began with a literature review, and after consulting experts, 35 different problems were identified under 11 main headings. These problems were then presented to 60 different healthcare facility managers for evaluation in terms of hygiene, cost, performance, and frequency. The responses from the facility managers were used to determine the severity of the problems and the importance of the components, resulting in a ranking system. According to this ranking, the most frequently encountered problems were switches placed near the speed regulator, momentary stops caused by the regulator, and working area size/safety. The study concludes that this research can help designers of new healthcare facilities avoid decisions that lead to unnecessary maintenance problems with cost impacts.

The article “Maintenance of lift systems affecting resident satisfaction in low-cost high-rise residential buildings” by Au-Yong, Azmi, and Mahassan (2017) aimed to examine the factors causing elevator problems that significantly affect the well-being of residents in low-cost, high-rise residential buildings. Interviews were conducted with three stakeholders (experts) to identify common problems in elevator malfunctions, and a survey was conducted to measure the level of resident satisfaction based on the identified key issues. The study found that the most common causes of elevator malfunctions were vandalism, improper use, poor workmanship during maintenance, and budget issues. Furthermore, the study concluded that proper maintenance alone is not sufficient for the correct functioning of the elevator system; therefore, it is crucial for all stakeholders to take appropriate precautions to ensure optimal maintenance results.

7. Results and Recommendations

In this study, in the first stage, a guideline was created for the pre-registration and post-registration periodic inspection of elevator applications in the building production process in Türkiye, within the scope of the current legislation. In the second stage, previous studies on the subject were examined. The findings and proposed solutions are presented below:

• Despite the broad legislative framework, there are inconsistencies between the legislation and its application. The main reasons for this can be said to be the ambiguity or lack of clarity in the legislative provisions and the insufficient deterrent effect of the sanctions.

• The guideline, which can serve as a roadmap for the proposed application in the operation of elevator application processes, can be detailed, and a more effective and efficient system can be created by integrating the parties involved in the process.

• While a green label is mandatory for elevators in the first periodic inspection in the current processes, this requirement is removed in the post-registration process. This situation is understood to make it difficult to ensure the effectiveness, efficiency, and sustainability of elevator applications in accordance with the legislation.

• According to the data in the literature, the most common problems encountered in elevators can be said to be door mechanisms, poor workmanship, budget constraints, user error, and inadequate supervision.

• The criteria for the initial pre-registration periodic inspection and the annual periodic inspection criteria should be separated and restructured to reflect the dynamics of each process.

• All parties must act simultaneously and consciously as a whole to ensure elevator safety. In this context, it is recommended that relevant parties be provided with training on the subject, and especially that building managers and apartment owners be included in this process.

• The necessary infrastructure should be created to ensure that the current inspection is carried out in accordance with the legislation, existing ambiguities in the legislation should be eliminated, and deterrent measures should be taken.

• It is recommended that risk analyses be conducted using data such as the Elevator Monitoring System (ASTAK), and that inspections be continuously revised accordingly.

• To extend the lifespan of elevators and minimize malfunctions, a proactive approach should be followed, and preventive mechanisms should be established to address potential malfunctions.

In conclusion, for safe elevator use in accordance with legal provisions, all stages, from the design phase to installation, initial periodic inspections registration and annual periodic inspections, need to be systematized. It is clear that this can only be achieved by establishing and properly operating mechanisms in accordance with the legislation. Coordinated work among all relevant parties and the continuous revision and updating of this system with evolving technology, based on the logic of continuous improvement, are crucial for sustainability.

Information Note and Acknowledgments

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Chapter 4

INVESTIGATION OF CAPILLARITY AND SOME MECHANICAL PROPERTIES OF BLOCK ELEMENTS PRODUCED USING VOLCANIC TUFF

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1. Introduction

This study, 10×10×10 mm³ solid blocks were produced using volcanic tuff aggregate. With the water absorption and capillarity experiments conducted on 28-day samples to determine some physical and mechanical properties of the light block elements produced, weight loss and strength loss occur this study, fully filled blocks of 10×10×10mm were produced using volcanic tuff aggregate. With the water absorption and capillarity experiments conducted on 28-day samples to determine some physical and mechanical properties of the light block elements produced, weight loss and strength loss occurring in tufa aggregate block elements under the influence of high temperature were determined. From the results obtained, in general, for the granulometry used (aggregate grain distribution), the changes in unit volume weight and compressive strength remained at a limited level. It has been determined that in block elements, after high temperature, weight loss and loss of compressive strength occur, regardless of the aggregate granulometry. The low unit volume weight values of the block elements produced support their use as a lightweight building material.

It has been demonstrated through studies in the literature that lightweight structures, which mitigate the effects of earthquakes, are both safer and more economical. Additionally, concrete or blocks produced using lightweight aggregates possess significant advantageous properties as building materials due to their low density, high thermal insulation, and excellent fire resistance [1]-[4].

In our country, addressing the housing deficit in the face of increasing population and inflation is essential for developing opportunities for individuals to work in a comfortable and peaceful environment, as well as for ensuring social welfare. To achieve this, it is crucial to resolve the issues related to construction. In terms of buildings, it is important to produce contemporary wall materials that can meet the needs of our country, which possess characteristics suitable for both internal and external environmental conditions, including thermal and acoustic insulation properties, and are resistant to physical, chemical, and biological effects, thereby adhering to the principles of building physics. In recent years, the problems associated with building physics have become more pronounced, highlighting the need for new composite building materials made from natural raw materials.

The use of volcanic-origin rocks such as andesite, basalt, and tuff has been increasingly prevalent in recent years within the construction sector for applications including plaster, fill wall materials, facade insulation cladding, paving stones, flooring, and concrete production. The growing adoption of these types of rocks in the construction industry is attributed to their thermal and acoustic insulation properties, as well as their superior hardness and strength compared to other carbonate rocks (such as calcite and dolomite) [5],[6].

Tuff is a general term for rocks that are considered sedimentary, formed from the sudden separation and cooling of magma ejected from a volcano, resulting in porous pyroclastic (fragmented by fire) particles due to the escape of gases contained within [7], [8].

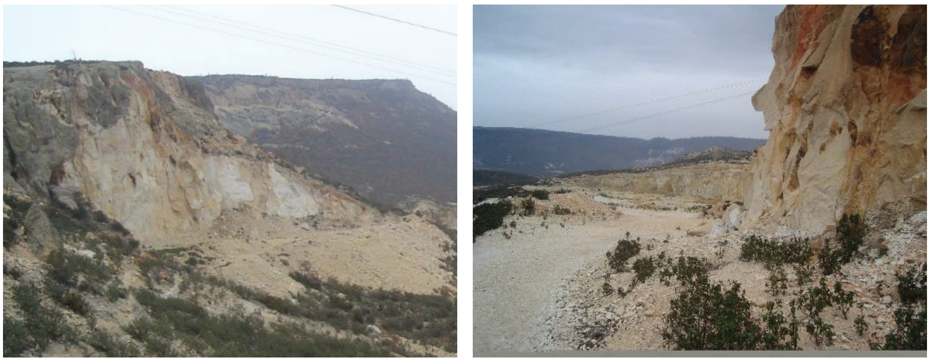

Figure 1. Afyonkarahisar - Seydiler volcanic tuff deposits.

Volcanic tuffs possess a significant local reserve capacity that can be utilized in the construction materials industry, both as rock and in the preparation of wall, lightweight concrete, or aerated concrete mortar. The average melting point of tuff is 1343°C. It does not undergo any changes below 760°C. At this temperature, the fibres on the outer surface crumple and contract. In flames ranging from 480 to 650°C, it does not experience structural degradation or fragmentation. The natural moisture content is very low. According to the Mohs hardness scale, its hardness ranges between 5.5 and 6. The compressive strength is between 95 and 130 kg/cm^2. Although glass has a specific density of 2.5 g/cm^3, the porous structure of tuff results in a density of less than 1 g/cm^3. Since the pore walls are separated by a membrane made of glass, tuff exhibits low permeability [9].

Historically, tuff has been utilized in various construction projects as a building material. These stones, which are relatively soft when extracted from quarries, can be easily removed and shaped. However, over time, exposure to air and sunlight causes them to lose moisture and harden [10]. The most significant component in the formation of the chemical properties of tuffs is SiO_2. The high or low value of this component indicates whether the tuff possesses acidic or basic characteristics [11], [12].

The Afyonkarahisar-Seydiler tuff, utilized as an aggregate material, is a dacitic tuff composed of various crystal fragments, quartz, plagioclase (oligoclase, andesite), biotite flakes, and opaque grains bound together by a glassy cement [13], [14].

Tuff aggregate is classified as a natural lightweight aggregate based on its general characteristics. Within the scope of the research, the production of lightweight block elements using tuff aggregate was carried out, and the samples obtained were examined for capillarity and certain mechanical properties.

The crushed volcanic tuffs, which are processed into aggregate through crushing and screening, possess a weight that is approximately one-third to one-half that of crushed stone, gravel, and sand. Consequently, concrete and block elements produced with tuff are lighter than standard concrete. Furthermore, when high-quality tuff and tuffite are ground, they yield a pure, white powder that contains sharp glass fibres and very fine fragments. During this grinding process, the particles break in a conchoidal manner. Even if smaller particles are formed during use, conchoidal shapes continue to persist. This characteristic of tuff is related to its hardness, making it an invaluable material for cleaning processes that involve rubbing and fine polishing.

Lightweight aggregate concretes possess excellent characteristics such as thermal insulation, sound absorption, and fire resistance, alongside the desired lightness in today's modern construction industry. Therefore, lightweight aggregate concretes and the prefabricated wall element panels made from these concretes are preferred building materials. They are still commonly used in the production of small precast structural elements and wall components. When lightweight aggregate concrete elements are utilized as wall components in a structure, it is possible to achieve an estimated cost saving of around 20% in transportation expenses, in addition to a reduction in dead loads due to their lightness, as well as an increase in the efficiency and speed of wall construction compared to normal aggregates [15].

Lightweight concretes containing tuff aggregate generally have higher water absorption values compared to concretes containing normal aggregate. This variation is dependent on the following factors:

- The percentage of clay and zeolite minerals contained,
- The glassy matrix that binds the particles and the void spaces between the particles,
- The degree of compaction and the amount of glassy phase present.

The aggregate obtained from tuff rocks, similar to other aggregates, influences the water absorption values based on granulation. Therefore, it is anticipated that aggregates with varying granulation will exhibit differences in their water absorption values [16].

2. Materials and Methods

The aggregates used in this study are natural lightweight aggregates that exhibit the general characteristics of tuff. The aim of the research is to investigate the variations in capillarity, water absorption rate, unit volume weight, and compressive strength values of lightweight block elements produced using volcanic tuff aggregates, depending on the aggregate granulometry (particle size distribution). The procedural steps for the laboratory studies are summarized and listed below.

• Volcanic tuff in sufficient quantities is to be sourced from nature in the form of rock, processed through crushing and screening to be rendered suitable for the production of block elements,

• After preparing trial mixtures for the tuff aggregate used in the study, the appropriate water/cement ratio, consistency, cement dosage, and suitable mixing method will be determined,

• Following the necessary mixture calculations to ascertain the effect of aggregate granulometry on the tuff aggregate block elements to be produced, experimental samples will be generated,

• Experimental studies will be conducted on the samples to determine the planned capillarity, water absorption rate, and resistance to high temperature and pressure, with results being obtained.

In the conducted experimental study, the tuff rock obtained from the Seydiler town in Afyonkarahisar was crushed and processed into particle sizes of 16-8 mm (coarse), 8-4 mm (medium), and 4-0 mm (fine), which were then utilized as aggregate for the mixture (Figure 2).

Figure 2. Images of the aggregates used in the study.

The tuff, obtained in the form of rock, was crushed using a jaw crusher and subsequently screened through standard sieves to produce lightweight aggregate of the desired particle sizes. The characteristics of the aggregates used have been determined in accordance with the principles outlined in TS 3529, and are presented in Table 1.

Table 1. Aggregate Properties

Aggregate Properties			
Particle Size (mm)	16-8 mm (large)	8-4 mm (medium)	4-0 mm (thin)
Loose Bulk Density (kg/dm³)	0.72	0.66	0.98
Compressed Bulk Density (kg/dm³)	0.86	0.78	1.19
Water Absorption Percentage (%)	26.20	30.25	-
Specific Gravity Factor (30 min.) (kg/dm³)	1.69	1.65	2.23

The production of lightweight block elements, PKÇ 42.5 type Portland composite cement has been utilized.

This study, the aggregate granulometry for blocks produced using volcanic tuff aggregate and previously conducted trial mixtures has been determined. Molds with dimensions of 100x100x100 mm were employed in the fabrication of the samples. The water/cement ratios in the mixture were maintained at 0.15, with cement quantities fixed at 220 kg/m^3. The tuff materials in their rock form were grouped after the crushing process through square mesh sieves, resulting in aggregate distributions of 16-8mm, 8-4mm, and 4-0mm, which were incorporated into the mixture. The block elements were produced using five different granulometries in a block-making machine with arms. All tests conducted on the samples were performed on block elements measuring 100x100x100 mm that had been cured in air for 28 days (Figure 3).

Figure 3. Visual related to samples of block with tuff aggregate.

Experiments conducted on block elements can determine the capillarity coefficient. For the capillarity (capillary water absorption) test, the lower parts of the side surfaces of the samples, which have reached a constant weight after drying in the oven, are insulated with paraffin to prevent water absorption (Figure 3.8). The purpose of paraffin coating the side surfaces is to ensure that water absorption occurs solely from the bottom surface area of the sample. The weights of the paraffin-coated samples are determined and recorded using a balance. The samples, placed in the experimental setup filled with water up to a certain level (the height of the paraffin-coated test sample), are weighed at 1, 4, 9, 16, 25, and 36 minutes after the start of the experiment, as indicated in Figure 3.9. As a result of these weighings, the amount of water absorbed per unit area is determined as a function of time. To ascertain the capillarity coefficient, the amounts of water absorbed per unit area are plotted on the vertical axis, while the square roots of the time values ($\sqrt{t}$) at which the weighings were conducted from the start of the experiment are plotted on the horizontal axis, resulting in a point graph. The slope of the linear graph drawn through these points is determined from the graph (S). This slope is then substituted into equation 1.1 to establish the capillarity coefficient [17].

Capillary Coefficient (k)(cm^2/dk) = $(\Pi/4) \times S^2 \times 10^5$ (1.1)

Figure 4. The steps for conducting the capillarity experiment.

A structure or its components should not be at risk of collapse under the effects of fire for a specified period after a fire has started. To ensure the safety of the occupants or to prevent the spread of the fire, if necessary, the building must remain standing during the burning of all fire loads and the cooling phase without collapsing [18].

In order to investigate the fire resistance of the produced blocks, high-temperature effect tests were conducted on 28-day samples. Three samples from each series were dried at 105°C before the high-temperature effect test and were brought to a constant oven-dry weight. The weights of the samples were measured, and they were placed in an oven with a heating rate of 6-10 °C/min. After the oven temperature reached 600 °C, they were heated for a duration of 2 hours (Figure 5). At the end of the heating period, the oven was turned off using the open-close button, and the samples were allowed to cool. Once sufficiently cooled, the samples were removed from the oven and left in the laboratory environment until they reached a constant weight.

In the laboratory setting, the cooled experimental samples were weighed using a scale with a precision of 0.1g, and their weights after exposure to high temperatures were recorded. Subsequently, to determine the pressure resistance value of the samples following high temperature exposure, a pressure strength test was conducted.

Figure 5. Samples with aggregate from tuff used for high temperature testing.

3. Results

This study investigates the variations in total water absorption, capillarity, weight loss after high temperatures, and compressive strength of block elements produced using volcanic tuff aggregate. The findings from this research are illustrated through the graphs provided below. The unit weight values of the block elements made with tuff aggregate range from 1344 kg/m3 to 1485 kg/m^3. no significant change in water absorption rate was observed in relation to the aggregate granulometry. For all samples, the total water absorption rate is approximately 20%.

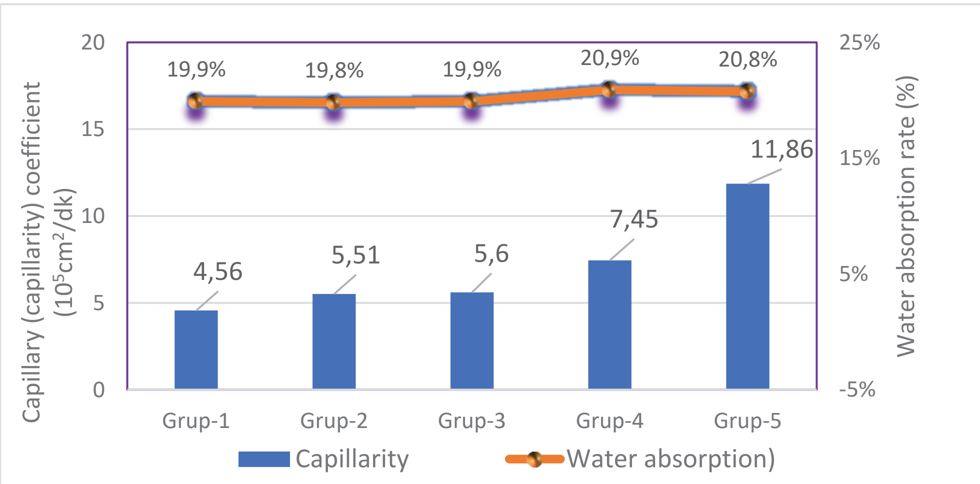

Figure 6. Changes observed in capillarity and water absorption rates.

According to the data obtained from the capillarity experiment conducted on the samples, the capillarity value has been identified to range from 4.6×10^5 cm/min to 11.9×10^5 cm/min. It is observed that as the proportion of fine material increases, the capillarity also shows an increase, as illustrated in the graph depicting the variation of capillarity (capillarity) rate shown in Figure 6.

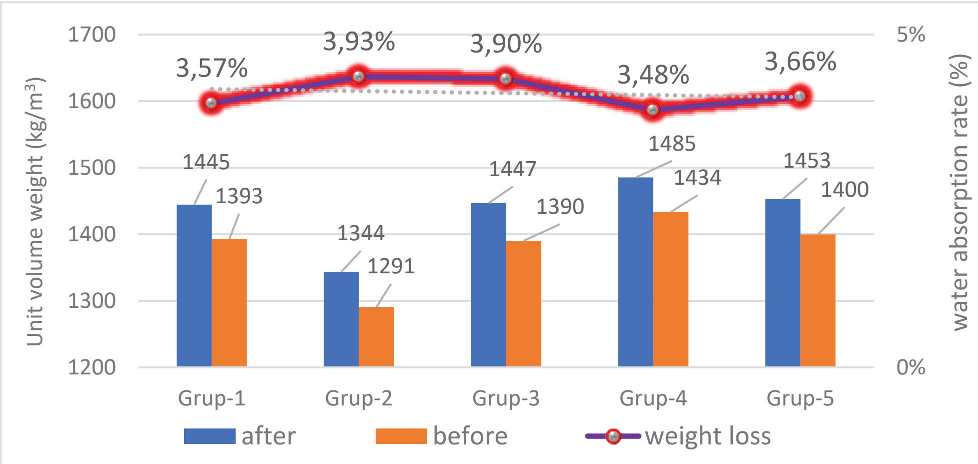

Figure 7. Change in unit volume weight before and after the high temperature experiment.

Determine the strength of block samples with tuf aggregate at elevated temperatures, samples that had cured for 28 days were subjected to a temperature of 600°C for 2 hours, after which they were allowed to cool to laboratory temperature. The weight losses of the cooled samples were measured using a scale, and the results were recorded. Additionally, to assess the changes in compressive strength due to the effects of high temperature on the same samples, compressive tests were conducted on cube samples measuring 100×100×100 mm. The obtained data is illustrated in the graphs presented in Figure 7. The results indicate that the weight loss after exposure to high temperatures varies between 3.48% and 3.93%.

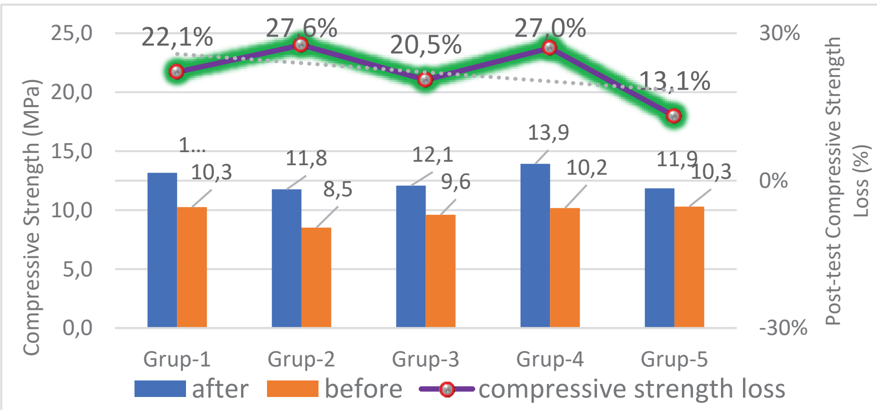

Figure 8. Change in pressure resistance before and after the high temperature experiment.

The average compressive strength value of the block elements with tuff aggregate has been found to vary between 13.2 MPa and 11.8 MPa. After the high-temperature effect, it is observed that significant reductions in compressive strength values have been recorded across all sample groups. The loss in compressive strength following the high-temperature test varies between 13.1% and 27.6% (Figure 8). It can be stated that the increase in the amount of fine material does not generally lead to a significant change in compressive strength, and the minor variations observed in the graph can be attributed to the compaction factor.

5. Conclusions

The tuffs formed by the accumulation of volcanic ash in various regions of our country are utilized in numerous areas of the construction sector, primarily in the production of insulation, plaster, and partition building elements.

This study aims to determine the changes in capillarity, water absorption, and weight and strength values after high temperatures of block elements made with volcanic tuff aggregate. When the results obtained are evaluated collectively, they indicate a high potential for the use of block elements produced with tuff aggregate in the construction sector, both as lightweight concrete aggregate and in the production of building blocks.

In block elements produced from tuff aggregate, regardless of aggregate particle size, both weight loss and a decrease in compressive strength are observed after exposure to high temperatures. The low unit volume weight of these block elements allows them to be used as lightweight building materials; however, this property may lead to a decrease in the (constant) vertical load performance of the structure, which offers economic advantages in terms of element sizing. Furthermore, this property will increase the structure's resistance to the effects of seismic forces.

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Chapter 5

FORENSIC ENGINEERING ASSESSMENT OF DESIGN MODIFICATIONS AND COST ESCALATION IN THE YUSUFELI DAM PROJECT

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I- Introduction

Yusufeli Dam represents one of the most prominent large-scale dam projects in Türkiye, both in terms of structural magnitude and the extent of design modifications and cost escalation observed during its implementation. Yusufeli Dam is a double-curvature concrete arch dam with a height of 270 m. A summary of the principal design changes and the resulting cost increases is presented below.

- **Tender pricing anomaly:** According to the approved final design cost estimate for tender (Volume 6-1, 2011), the concrete unit cost for Yusufeli Dam was 144 TL/m³. Nevertheless, the contract was awarded to the Cengiz–Limak–Kolin consortium, which bid 28.19 TL/m³ for concrete.
- **Impracticable concrete price:** Producing concrete at this unit price was technically and economically infeasible. Consequently, before dam body concreting began, measures were required to consume the contract amount through other work items.
- **Artificial reduction of foundation parameters:** Consultants Quentin Shaw and Johannes Kleberger, known from the Çine Dam project, were engaged. A justification was introduced claiming that the foundation deformation modulus was approximately half of its actual value, thereby necessitating extensive bedding concrete. This claim is contradicted by the approved final design, reports by Harza's senior consultant David Kleiner, studies conducted by JICA and EİE, and comparisons with the nearby Deriner and Artvin Kemer dams.
- **Increase in excavation and anchoring quantities:** Based on inflated excavation quantities and artificially widened fault zones, the number of prestressed anchors—among the most expensive foundation elements—increased by approximately 60 times. Together with other revisions, the approved cost estimate was fully exhausted before dam body concreting commenced.
- **Work completion tender and price escalation:** During the work-completion tender phase, despite cumulative inflation of 64% between 2012 and 2018, the concrete unit price was increased by 448%, and the contract was again awarded to Limak Construction. Prestressed anchor unit prices also increased by approximately 140% in USD terms.
- **Excessive use of prestressed anchors:** As anchoring became highly profitable and ground conditions continued to be portrayed as weaker than reality—despite official reports indicating that the assumed fault widths were incorrect—prestressed anchors were installed extensively across the foundation. The total cost of anchoring works reached approximately USD 400 million.
- **Spillway design changes:** The spillway was originally designed with five gates. Although a wider spillway was feasible, the gate height was increased instead. After the plunge pool lining and downstream works were completed for the five-gate configuration, two gates were cancelled near project completion, based on erroneous test interpretations.
- **Construction of spillway tunnels:** To replace the cancelled gates, two spillway tunnels were constructed at an additional cost of approximately USD 200 million.
- **Expansion of consolidation grouting:** Poorly defined ground conditions were also used to justify a substantial and disproportionate increase in consolidation grouting quantities, further contributing to cost escalation.

These issues are examined in chronological sequence to clarify how the identified design changes evolved in relation to construction progress and to assess the underlying reasons for their implementation.

II- Project and Cost Modifications Based on Unverified Technical Justifications

1) According to the approved final design and bill of quantities prepared for tender (DSI, 2011), the unit cost of concrete for the Yusufeli Dam project was determined as 144 TL/m³. Despite this approved estimate, the construction contract was awarded to the Cengiz–Limak–Kolin consortium, which submitted a bid corresponding to a concrete unit price of 28.19 TL/m³ (DSI, 2012).

From a forensic engineering and construction economics perspective, this unit price was not compatible with feasible concrete production, given material, energy, labor, and logistics costs prevailing at the time. Under such conditions, recovery of project costs through standard dam body concreting was technically impossible. This circumstance created a structural incentive to increase quantities and introduce design modifications prior to the commencement of dam body concrete works in order to compensate for the unrealistically low bid.

2) Before concreting began, Shaw from ARQ and Kleberger from IC Consulting, consultants previously involved in the Çine Dam project, were retained. Subsequently, a technical justification was introduced asserting that the deformation modulus of the dam foundation rock mass was approximately 50% lower than its actual value, thereby requiring the placement of extensive foundation bedding concrete.

This assumption about deformation modulus is not supported by independent or authoritative technical evidence. A review of the approved final design documents (DSI, 2011), the report prepared by Kleiner (2006), senior consultant of Harza Engineering, and geological and geotechnical investigations conducted for Yusufeli Dam (EİE, 1990a) demonstrate that the adopted deformation parameters were inconsistent with documented site conditions. Furthermore, comparative evaluation with the Deriner Dam (1986) and Artvin Arch Dam (EİE, 1990b), located immediately downstream and founded on comparable geological formations, indicates no justification for the substantially reduced foundation stiffness values assumed for Yusufeli Dam.

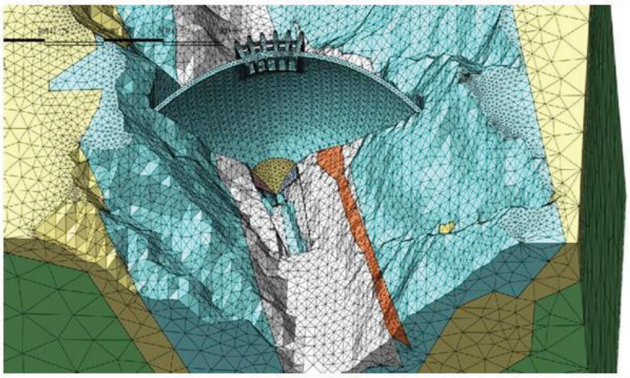
In the Feasibility Report (DSI, 1986), the dam foundation was classified into three categories—A1, A2, and B. The A1 foundation class exhibits a deformation modulus ranging from 6.8 to 11.4 GPa, the A2 foundation class ranges from 8.6 to 14.2 GPa, and the B foundation class ranges from 2.9 to 7.8 GPa.

The elastic modulus values determined by IC Consulting, together with the color-coded zones used in the geotechnical model, are, as shown in Figure 1, consistent with and close to the values reported by DSI (1986). The DSI values themselves are based on plate load test results conducted by EİE. The diameter of the plate loading equipment used in these tests was approximately 30–35 cm.

Tablo 2: Kaya kütlesi özellikleri (IC – Ağustos 2015[2])

Temel Malzemesi (FM)	Elastisite Modülü E (GPa)	Poison Oranı	Renk
0	13	0.27	
1	11	0.28	
2	8.5	0.29	
3	6.0	0.30	
4	3.5	0.31	

Ağustos 2015 IC raporundan[2] yorumlandığı şekilde, yukarıdaki kaya kütlesi malzemelerinin, FE modeline uygulanmış, ilk, basitleştirilmiş dağılımları, Şekil 10'da gösterilmektedir.



Temel Malzemesi	FM0	FM1	FM2	FM3	FM4
Elastisite Modülü (GPa)	13	11	8.5	6	3.5

Figure 1. Elastic modulus values determined by IC Consulting and the color-coded zones used in the geotechnical model.

At Deriner Dam, plate load tests conducted by EİE using the same testing apparatus indicated a deformation modulus of approximately 5.1 GPa, whereas a value of 9 GPa was adopted in the design calculations (Yılmaz et al., 2021; Stucky, 2000).

One contributing factor to this discrepancy is the limited diameter of the plate loading device, which makes the test results highly sensitive to excavation-disturbed zones near the surface. Another factor is the application of the Boussinesq and Vogt equations, which may not be fully applicable to jointed or discontinuous rock mass systems. As a consequence, back-calculations performed after the dam was put into operation indicate deformation modulus values that are approximately twice those obtained from the initial plate load tests (Yilmaz et al., 2021).

In order to justify the use of low deformation (or elastic) modulus values, seismic velocity measurements were deliberately conducted in excavated areas, as documented in the report (Belirti Engineering and Consulting, 2016).

As explained in our previously published study (Yılmaz et al., 2021), excavations carried out to reach the foundation level inevitably induce blast-related damage in the rock mass and create a loosening zone due to stress relief. For excavations with moderate slope angles, the depth of the loosening zone can be reasonably approximated as one-and-a-half times the thickness of the excavated rock divided by 1.5.

However, at locations such as the Yusufeli Dam—where steep excavation slopes are present and where, as shown in the Figures 2 and 3, a large horizontal platform was created at elevation 715 m, followed by excavations continuing downward in two directions at sharp inclinations—the loosening zone depth and/or valley-parallel cracking can extend to significantly greater depths. In our assessment, this mechanism explains why low shear-wave velocities were measured at excavation depths reaching up to 136 m. Moreover, these velocities were interpreted and presented as being lower than warranted.

Figure 2. Seismic velocity measurements at Yusufeli Dam conducted in areas affected by excavations (each bench approximately 15 m in height).

In addition, due to high ambient noise levels at the measurement sites and the low mass of the dropped hammer, it was frequently not possible to achieve frequencies below 10 Hz, further compromising data quality. These measured low velocities therefore do not indicate inherently weak rock properties, but rather reflect rock mass conditions that were heavily disturbed by excavation and blasting activities.

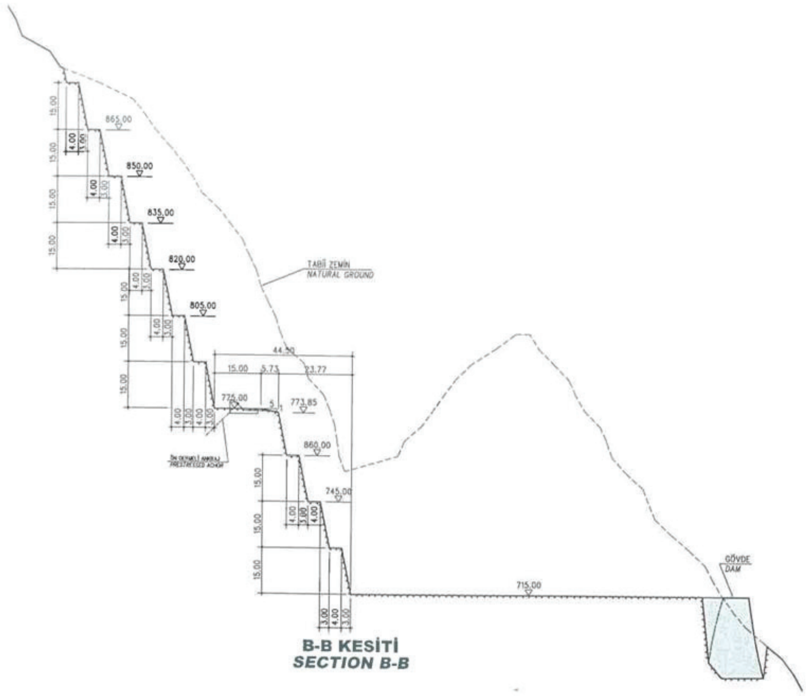


Figure 3. View of the natural ground elevation on the left abutment of Yusufeli Dam prior to excavation on the 715 m platform where seismic velocity measurements were conducted.

According to the investigations conducted by Belirti Engineering and IC Consulting (2016), seismic wave velocity measurements were carried out along selected profiles within the Yusufeli Dam site. When these seismic profiles are evaluated in conjunction with excavation depth data from the same locations, the results clearly demonstrate that greater excavation depths correspond to a deeper transition to undisturbed (intact) rock mass conditions (Figure 4).

In practical terms, increasing excavation depth leads to a thickening of the relaxation (loosening) zone, within which fracture density increases and seismic wave velocities (Vp and Vs) decrease. As a consequence, the depth at which competent bedrock is encountered increases in approximate proportion to the excavation depth.

These observations confirm an inverse relationship between seismic velocity and the thickness of the excavation-induced damage zone. From a forensic and design standpoint, the findings underscore the necessity of explicitly accounting for depth–velocity correlations during both the design and construction phases, particularly when seismic velocity data are used to infer in situ rock mass properties.

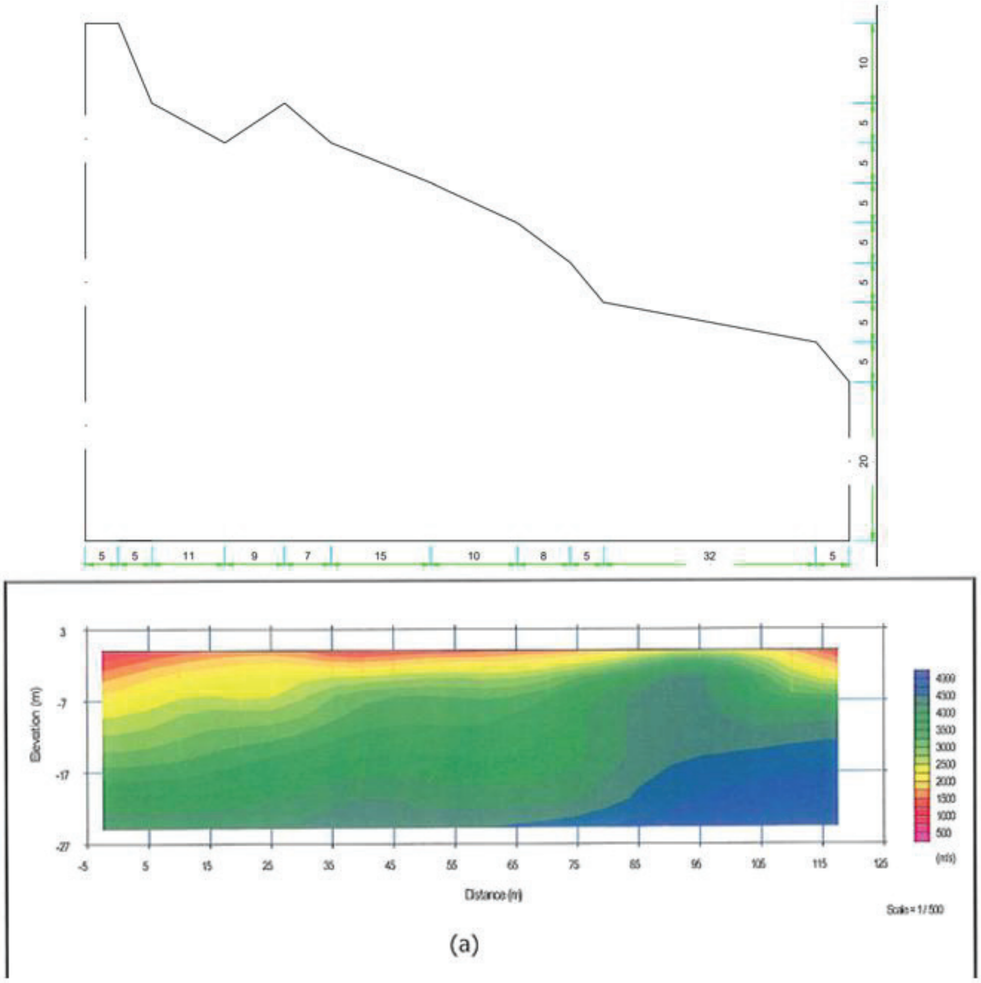


Figure 4. Relationship between excavation depth and the depth to intact bedrock (indicated in blue), based on seismic velocity data from Belirti Engineering and Consulting (2016).

If the primary objective of the seismic investigations had been to determine the undisturbed geotechnical properties of the foundation, seismic measurements would have been carried out between galleries (tunnels) already excavated within the dam foundation. Such measurements would have provided velocity data from rock masses unaffected by excavation damage. In practice, geotechnical engineers often prefer to conduct seismic velocity measurements between boreholes for precisely this reason.

At the Yusufeli Dam, despite the existence of galleries that would have allowed such measurements, this approach was not adopted. Instead, seismic surveys were conducted on excavated surfaces, a choice that can only be interpreted as serving the purpose of portraying the foundation as having poorer mechanical properties than it actually possesses. Subsequently, after extensive excavations had already been completed, seismic velocity measurements were conducted between galleries, apparently to demonstrate that “sufficient” seismic velocities had eventually been achieved. However, once the initial measurements were taken at inappropriate locations and used to justify design decisions, such later measurements are forensically irrelevant.

The use of these incorrectly located low-velocity measurements in developing the geotechnical model is explicitly demonstrated in a presentation delivered by IC Consulting, the dam’s consultant, on 30 January 2024 in Trondheim, Norway (the MASW velocity map shown in color at the center-left of the Figure 5).

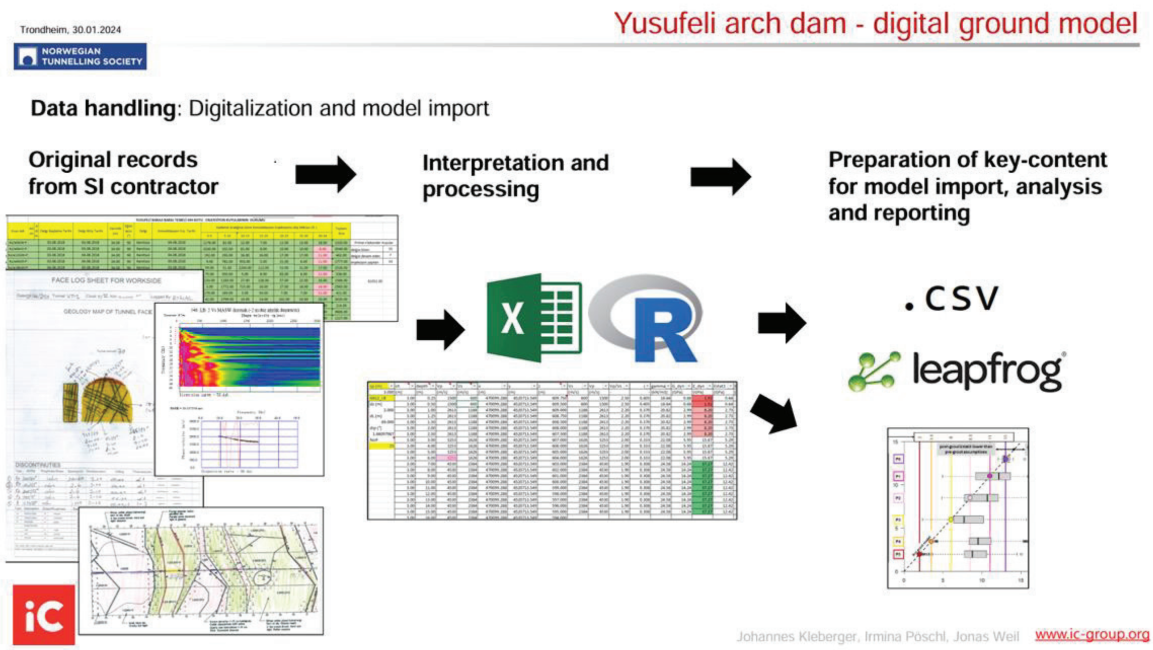


Figure 5. lide extracted from a presentation presented by IC Consulting, acting as the dam's consultant, on 30 January 2024 in Trondheim, Norway.

In conclusion, seismic velocity measurements were intentionally conducted in excavation-disturbed zones to depict the foundation as having inferior properties. The resulting data were then used as justification for adopting artificially low deformation modulus values, which in turn served as the basis for additional excavation and the use of bedding concrete beneath the dam body. As will be explained in subsequent sections, the claimed loss of stability associated with these additional excavations was later cited as one of the justifications for the installation of prestressed anchors at unit prices many times higher than international benchmarks and comparable Turkish projects.

3) Despite all these assessments, IC effectively enabled the ARQ recommendation to increase excavation quantities and to introduce concrete bedding beneath the dam foundation by artificially enlarging fault zone widths and adopting deformation modulus values significantly lower than those warranted by the site conditions. In the tender-design documents approved in December 2011, the faults were intended to be treated through concrete infilling and grouting just like Deriner Dam rather than by extensive excavation and replacement. One of the principal reasons for this approach was that the calculated deformation modulus of the fault zones was higher, while the assumed fault widths were considerably narrower.

4) Despite these objections, the static and dynamic analyses of the dam were ultimately carried out assuming enlarged fault zones as shown in Figure 6 and reduced deformation modulus values without taking into account DSI objections as shown in Figure 7. Based on these analyses, a decision was taken to use concrete bedding beneath the dam body, as documented in the Report on the Necessity of Dam Body Foundation Strengthening. Consequently, this decision led to simultaneous increases in excavation volumes, concrete quantities, and the number of prestressed anchors.

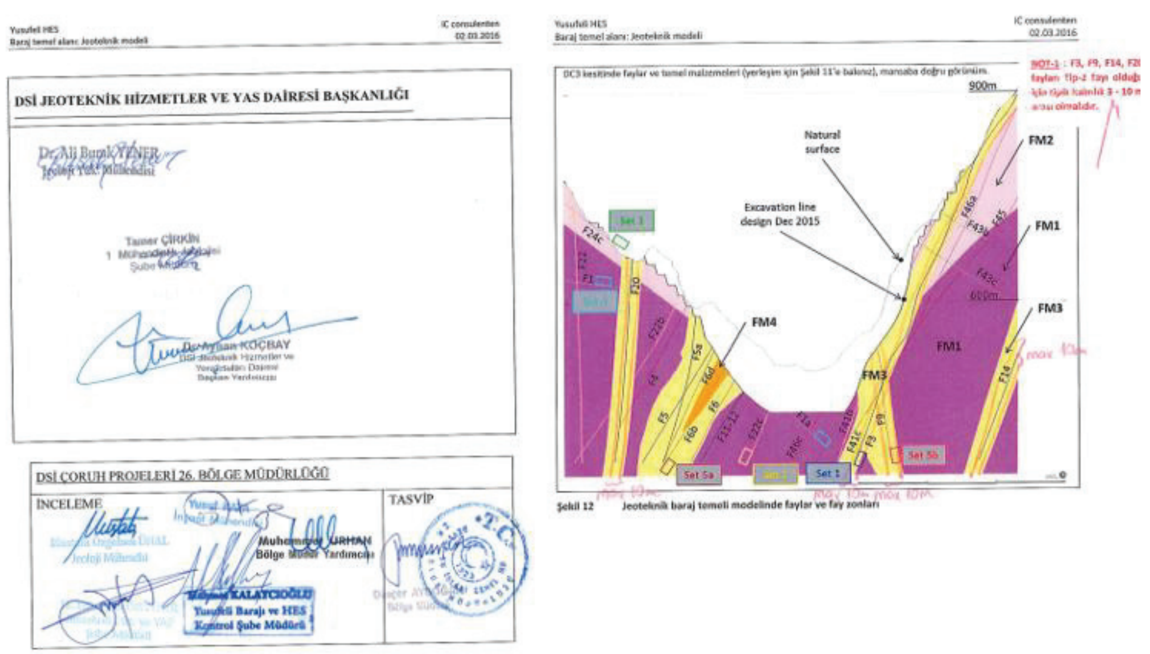


Figure 6. The geotechnical model prepared by IC Consulting, which was not approved by DSİ due to the assumed fault widths.

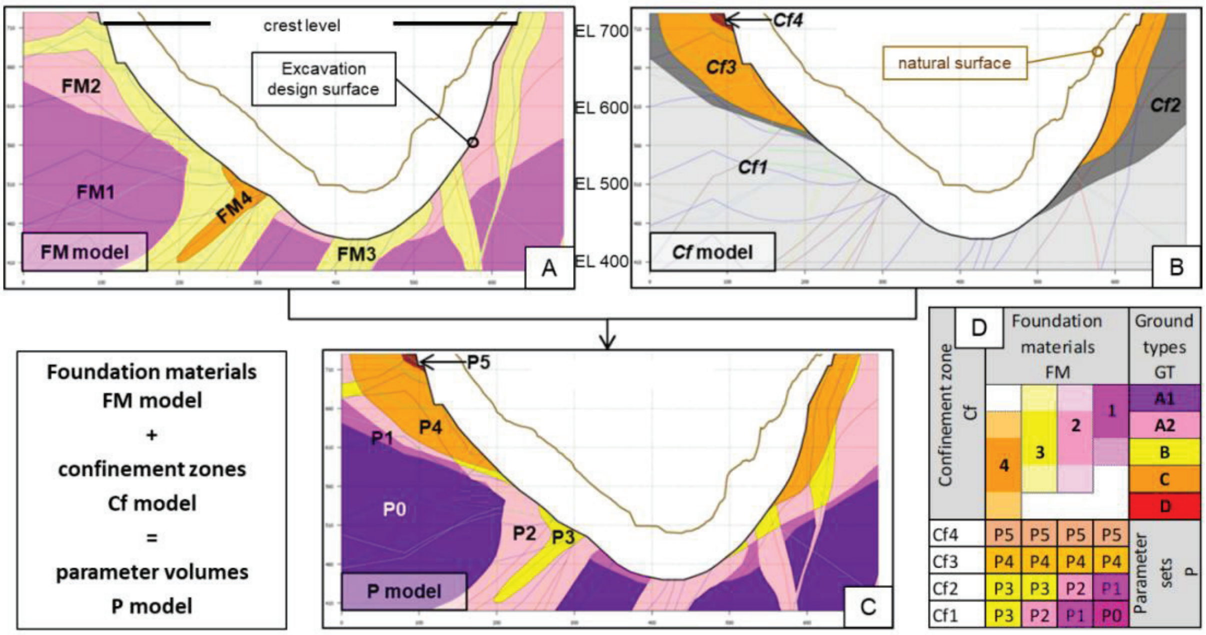


Figure 7. Geotechnical model used in the finite element analysis of the dam (After Kelberger et al., 2023).

5) Based on these changes in geotechnical model, excavation quantities were significantly increased. As a direct consequence, the quantity of prestressed rock anchors, which represent one of the most expensive foundation treatment elements, increased by approximately a factor of sixty relative to the original design. Together with additional design revisions, these changes resulted in the complete consumption of the approved cost of the dam prior to the initiation of dam body concrete placement.

6) Although overall inflation between 2012 and 2018 amounted to approximately 64%, the contract-extension tender resulted in a 448% increase in concrete unit prices, a deviation well beyond inflationary justification, and the additional works were again awarded to Limak Construction.

Concurrently, prestressed anchor prices of 2012 contract (Table 1 and 2) rose by roughly 140%, reaching USD 64,083 for a 50 m, 12-strand anchor, compounding the financial impact of the modified design assumptions.

7) Subsequent to 2018, anchor unit prices were further increased by approximately 33%, resulting in a unit cost of USD 1,708/m and a total cost of USD 85,423 for a 50 m anchor. However, the unit prices of the prestressed anchors at Ermenek Dam were determined by the Public Works Board through Decision No. 2007/06 dated 30.05.2007. For these anchors—63 in total, each with a working capacity of 150 tons, constructed under very difficult conditions using cable cranes (Figure 8)—the unit price was set at €362.68 per meter. This amount corresponds to approximately USD 400 per meter in today's terms. The unit price determined for the Yusufeli Dam is therefore more than four times higher than this reference value.

The conclusion drawn from all these explanations is that, regardless of whether cable anchors are constructed using cable cranes as at Ermenek Dam (for which the prices applied at Yusufeli Dam were increased by a factor of three), single-bar anchors are used, the unit prices prepared by the General Directorate of Highways (KGM) for cable anchors are taken as reference, or prevailing market prices are considered, the unit prices applied in the Yusufeli Dam completion works are at least five times higher than the prices that would be technically and economically justified.

Table 1. Weight Breakdown of a Prestressed Anchor at Yusufeli Dam

Item	**Unit Weight (kg/m)**
Prestressing strand	17.17
Sheath and injection pipe	4.3583
Corrugated pipe	1.64
Grease oil	0.057
Anchor compound	0.086
Inner centralizer	0.32
Outer centralizer	0.32
Steel bearing plate	0.208
45×45×5 steel plate	2.271
Anchor protective head	0.143
Total weight (kg/m)	26.5733

Table 2. Cost Breakdown of a 50m Prestressed Anchor at Yusufeli Dam

Parameter	**Value**
2018 unit price (TL/kg)	37.82
Cost per meter (TL/m)	1,005.00
March 2018 exchange rate (USD/TL)	1.88
Cost per meter (USD/m)	534.58
Total cost for 50 m (USD)	26,728.78

Despite official reports indicating that the assumed fault widths and rock mass conditions were inconsistent with observed geological data, the substantially increased profitability of anchorage works led to the extensive use of prestressed anchors across large portions of the foundation. This implementation was based on reports prepared by the IC consultancy firm (2016), which adopted enlarged fault widths, reduced deformation modulus values, and lower rock shear strengths. Consequently, the total cost of anchoring works reached approximately USD 400 million, which far exceeded the initial tender cost of the dam, estimated at about USD 286 million.

Figure 8. Construction conditions of the prestressed anchors at Ermenek Dam.

8) The spillway system was originally designed with five radial gates. Although alternative configurations allowing a wider spillway width were feasible, the selected design employed significantly increased gate heights. After the downstream stilling basin and all associated lining and structural works had been completed in accordance with the five-gate configuration, and shortly before project completion, two gates were cancelled. This decision was reportedly based on incorrect or misinterpreted test results. In lieu of the cancelled gates, two spillway tunnels were constructed, resulting in an additional cost of approximately USD 200 million.

Yılmaz et al. (2024) demonstrate that the spillway design decisions for the Yusufeli Dam were largely driven by 1:40 scale physical model tests carried out by DSİ in 2015. Although these tests suggested impact pressures at the plunge pool approaching full free-fall values under PMF conditions, the results were significantly influenced by the inherent scale limitations of Froude similitude. Consequently, key prototype phenomena—such as turbulence development, jet disintegration, and air entrainment—were not adequately reproduced, rendering the measured pressures unrepresentative of actual dam behavior.

Notwithstanding the availability of numerical simulations, empirical formulations, and alternative design configurations, all of which consistently predicted substantially lower impact pressures, the physical findings were accorded decisive weight. This reliance led to excessively conservative design assumptions, including disproportionate plunge pool protection measures and a fundamental modification of the spillway layout. In particular, two of the five originally planned spillway gates were eliminated and replaced by two additional tunnels, resulting in an estimated 20% increase in the overall project cost.

From a forensic engineering standpoint, the spillway redesign and the associated cost escalation are attributable to an overreliance on scale-affected physical model data and its misinterpretation, rather than to hydraulic requirements dictated by prototype flow conditions.

- **Measured Dynamic Pressures on The Physical Model**

It was stated that by Shaw (2024) "In fact, the maximum dynamic pressures measured on the physical model, of approximately 50% of the free-fall height, were the result of local concentrations and 3-dimensional effects that resulted from the need to focus the discharge jets from five spillway bays into an undersized, asymmetrical plunge pool." Unfortunately, this explanation was not verified by the results published by DSI and referenced in our article (Poyraz, 2016).

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Test results are shown in Table 3. I have not translated it into English to preserve the originality of the document, but it remains understandable. The table presents pressures at the bottom of the plunge pool for various flow values from the spillway at the crest.

Table 3. Pressures at the bottom of the plunge pool for various flow values (Poyraz, 2016).

Feyezan Debileri	Ortalama Basınç Yüksekliği (m)	Orijinal Durumda Dinamik Basınç Salınımları P/γ (m)							
		5	6	16	17	18	19	29	30
Q_2= 504 m³/s	48,03	0,42	0,44	0,23	0,20	0,25	0,22	0,55	0,62
Q_{10}= 893 m³/s	49,65	5,16	3,12	2,82	2,11	1,65	1,20	1,43	2,00
Q_{100}= 1821 m³/s	52,25	10,97	17,41	9,78	33,73	32,33	14,37	10,49	13,64
Q_{500}= 2463 m³/s	52,88	28,15	35,75	18,53	44,02	71,32	67,36	19,12	36,79
$Q_{1.000}$= 2739 m³/s	53,64	25,99	27,46	15,28	36,11	37,30	42,56	14,23	17,25
$Q_{10.000}$= 3106 m³/s	55,11	105,93	83,38	64,80	102,26	102,57	49,55	38,11	34,68
Q_{OEBT}= 5084 m³/s	59,73	143,28	117,95	56,56	**148,65**	**204,88**	**154,47**	42,81	55,44

- **Possible to Build a Wider Spillway**

The spillway configuration was examined in detail from the initial final design stage through the modifications implemented during construction. As part of this review, Dr. Yılmaz directly consulted engineers involved in the original final design to clarify whether geometric constraints had limited spillway widening. The engineers stated that they had formally proposed widening the spillway to significantly reduce the flow per meter, but DSİ did not approve this proposal, even though there were no structural or geometric constraints at the dam crest that would have prevented a wider spillway.

Furthermore, the plunge pool as constructed is approximately 40% wider than specified in the approved final design (Figures 9 and 10), demonstrating that additional lateral space was, in practice, available. In addition, a combined assessment of the photographic evidence presented by Dr. Shaw (2024) and the design modifications executed downstream during construction indicate that the area surrounding the plunge pool likewise provided sufficient space to accommodate a wider spillway configuration.

From a hydraulic standpoint, increasing the spillway width would have significantly reduced unit discharge, thereby promoting greater jet spreading and enhanced air entrainment. These mechanisms would have resulted in lower dynamic impact pressures on the plunge pool floor, owing to both jet diffusion and entrained air cushioning. Moreover, an increased free-fall length of the jet would be expected to further reduce impact pressures through surface instabilities and progressive jet breakup during descent.

Accordingly, the adopted spillway configuration—characterized by a narrow, coherent, and largely unaerated jet—was not a hydraulic necessity, but rather the consequence of design choices made despite the availability of technically viable and less aggressive alternatives.

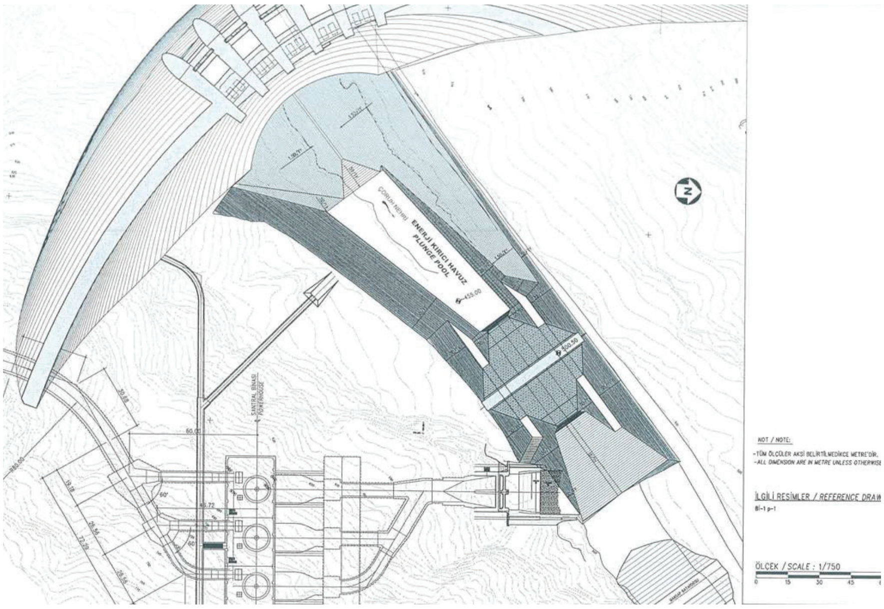

Figure 9. Plunge pool with respect to other structures (According to the final design, 2012).

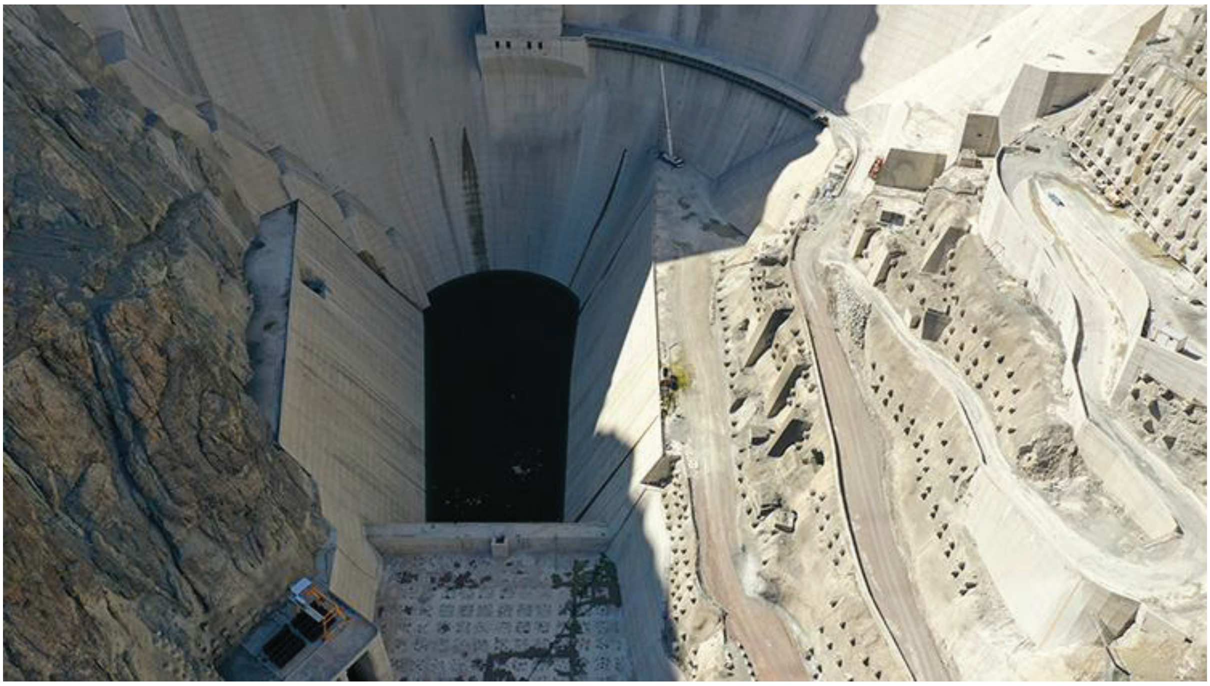

Figure 10. Yusufeli Dam Plunge Pool (Picture from Anadolu News Agency)

The plunge pool has a minimum top width of approximately 80 m, as illustrated in Figure 10. Moreover, a substantial portion of the plunge pool side slopes above the maximum operating water level was subsequently lined with concrete despite this feature not being accounted for in the approved final design. This post-design modification indicates that additional structural capacity and geometric flexibility were available at the plunge pool margins, which were not considered during the original hydraulic design and evaluation process.

Consequently, there was sufficient space to accommodate a wider spillway. This was highlighted in Yilmaz et al. (2024), which noted, *“There was room to reduce the height of the spillway and increase its width, as suggested by the designer in 2011. This would have enhanced the effectiveness of the teeth and lips, aiding in flow aeration and reducing pressures on the plunge pool's bottom between the time the tests were conducted and when the dam's concrete reached the spillway elevation.”* Therefore, the overlapping effects of the jets did not need to be considered for the CFD analysis.

- The Size of The Plunge Pool

Roberts Splitter configurations were incorporated into the Yusufeli Dam spillway design (Figure 11). In South Africa, such arrangements were successfully implemented under unit discharge rates of 41.8, 61.3, and 66.8 m³/m/s at the Hazelmere, Vanderkloof, and Gariep dams, respectively. More recent projects, including the Victoria Dam in Sri Lanka and the Wadi Dayqah Dam in Oman, extended these applications to even higher unit discharges of approximately 80 and 87 m³/m/s.

It is noted, however, that at both the Victoria and Wadi Dayqah projects, progressive adjustments to the geometry of the splitter teeth and the downstream lip were required during physical model testing in order to achieve optimal hydraulic performance. This experience underscores that effective implementation of Roberts Splitter systems at high unit discharges depends on iterative geometric optimization, rather than on a fixed, unmodified design configuration.

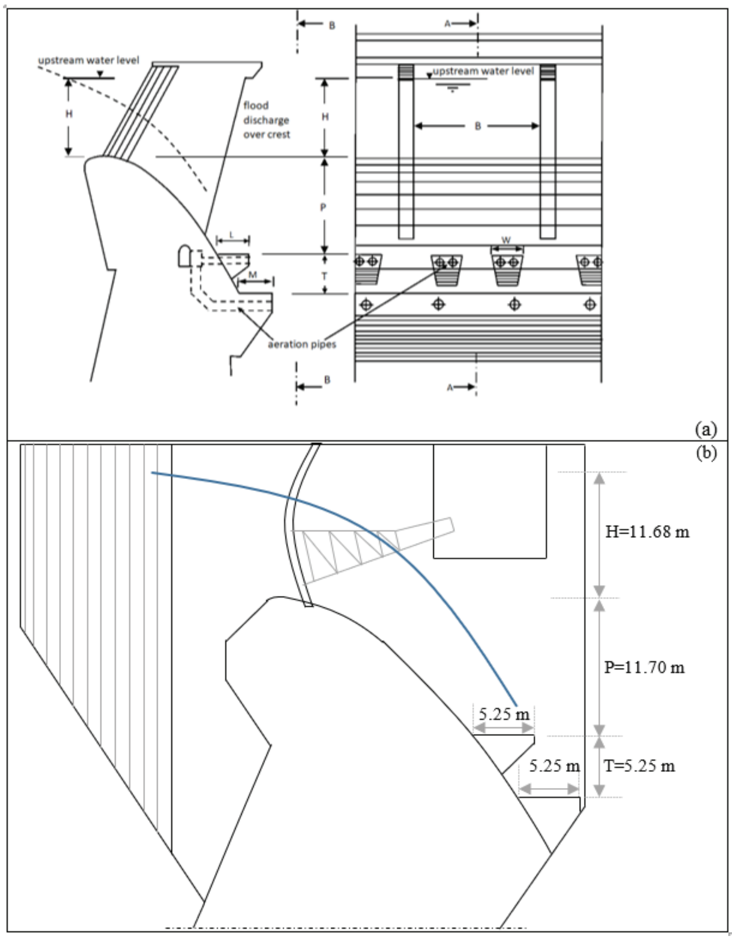

Fig.11. Typical layout of a spillway (Panel (a) shows the Roberts Splitters; M and L show the length of the lip and the length of downstream teeth, respectively. Panel (b) shows the lips and teeth in the Yusufeli Dam.) After Yilmaz et al. (2024).

Model tests conducted on the 196 m long central spillway of the Wadi Dayqah Dam demonstrated satisfactory hydraulic performance at unit discharges of up to 84.2 $m^3/m/s$, corresponding to a total discharge of 16,500 m^3/s over the central spillway section (Hieatt et al., 2010). Under probable maximum flood (PMF) conditions, the unit discharge further increased to approximately 87 $m^3/m/s$ for a total discharge of 18,400 m^3/s.

Similarly, the Victoria Dam spillway design comprises eight counterbalanced radial gates, each 12.5 m wide and 9 m high, with a total discharge capacity of 8,000 m^3/s (Back and Mee, 1991). This configuration results in a unit discharge of approximately 80 $m^3/m/s$, which has been demonstrated to operate satisfactorily.

At Yusufeli Dam Design, the design flood of 5,084 m^3/s is discharged through five spillway openings, each 11.5 m wide, yielding a discharge of 1,016.8 m^3/s per opening and a corresponding unit discharge of 88.4 $m^3/m/s$. This value is therefore fully consistent with established international precedent. Furthermore, the orientation of the spillway openings at the crest of Yusufeli Dam could have been adjusted to mitigate downstream jet concentration. This conclusion is supported by the fact that a concrete-lined plunge pool approximately 40% wider than that specified in the final design was ultimately constructed, demonstrating that adequate downstream space was available.

From a hydraulic standpoint, a properly configured spillway with sufficient width, optimized crest geometry, and effective aeration would have caused the plunging jets to break up and entrain air before reaching the plunge pool, significantly reducing dynamic impact pressures. This behavior has been quantitatively demonstrated by Yılmaz et al. (2024).

Dr. Shaw (2024) further notes that, in the adopted configuration, five concentrated spillway jets were focused onto an effective plunge pool impact area of only approximately 300 m^2, while the plunge pool water volume was limited to about 500,000 m^3. This resulted in an estimated specific energy dissipation demand of approximately 20 kW/m^3 during the PMF, a value that substantially exceeds the 7–9 kW/m^3 limit recommended by Mason (2011) for plunge pool design.

This so-called "raw" power requirement was computed using $P = \rho g Q H$,

where P is dissipated power, ρ is water density, g is gravitational acceleration, Q is discharge, and H is the effective fall height. However, this formulation does not account for energy losses due to jet aeration, air entrainment, and progressive jet disintegration during free fall (CFBR, 2021). Numerous studies, including those by Luis and Castillo (2007) and Castillo et al. (2014), have shown that such mechanisms can lead to substantial reductions in effective impact energy, depending on jet geometry and aeration conditions.

In Yılmaz et al. (2024), the characteristic breakup length L_b and jet diameter D_j were calculated as 77 m and 4.16 m, respectively. For ratios of $2 \leq H/L_b \leq 3$, the mean dynamic pressure coefficient at plunge pool entry may be as low as 0.2 when the jet is properly aerated, whereas it may reach approximately 0.75 in the absence of adequate aeration as shown in Figure 12. In practical terms, this implies that only 20–25% of the raw energy would reach the plunge pool under aerated conditions, compared to up to 75% without aeration. The design drawings (figure 11) show that Roberts Splitters, spillway teeth, and an aeration system were in fact incorporated into the Yusufeli Dam design specifically to promote jet spreading and breakup.

It is also relevant to note that Jehano et al. (2010) reported that allowable specific energy dissipation values can reach 30 kW/m³ for natural plunge pools and up to 60 kW/m³ for concrete-lined plunge pools, provided that appropriate design precautions are implemented. The plunge pool at Yusufeli Dam is fully concrete lined, and the limits proposed by Mason (2011) were primarily intended for unlined plunge pools.

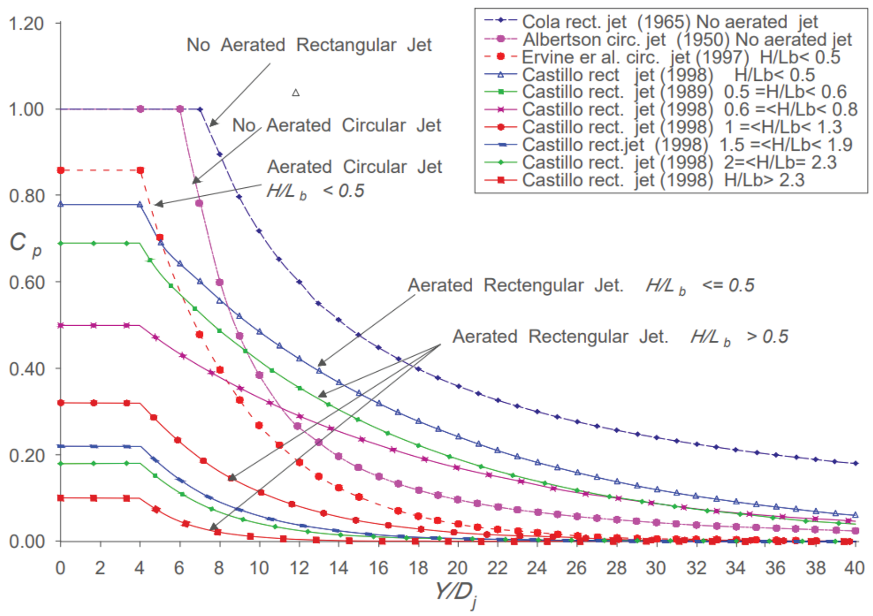

Figure 12. Mean dynamic pressure coefficient C_P versus Y/B_j or Y/D_j pool depth to/impact diameter (Luis and Castillo, 2007).

- **Forensic Conclusion About Spillway Design Change**

Based on international precedent, numerical and empirical studies, and the geometric flexibility available both at the crest and downstream of the dam, the spillway jets at Yusufeli Dam could and should have been properly aerated and dispersed, thereby significantly reducing dynamic pressures in the plunge pool. Sufficient space existed to widen the spillway and prevent excessive jet concentration. Even under conservative assumptions, the design would have remained within the acceptable energy dissipation limits identified by Jehano et al. (2010) for lined plunge pools.

Accordingly, the decision to cancel two spillway gates and replace them with two spillway tunnels, at an additional cost of approximately USD 200 million, cannot be justified on hydraulic or design-safety grounds. From a forensic perspective, this cost escalation resulted from avoidable design decisions rather than unavoidable hydraulic constraints.

9) Finally, inadequately defined foundation conditions were also used to justify a substantial increase in consolidation grouting operations. The lack of clear geotechnical boundaries and performance criteria led to a disproportionate expansion of grouting quantities, further contributing to cost escalation without corresponding demonstrable improvements in foundation performance.

In valleys formed by fluvial erosion, the depth of the excavation-induced loosening zone and the foundation excavation limit are generally determined using a combination of borehole data, seismic velocity measurements, and water pressure (Lugeon) tests. At both Deriner and Yusufeli Dams, the excavation limits defined in the approved final designs were established in a manner consistent with borehole and water test data, such that at least the upper 50 m of the foundation rock mass was excavated (Yilmaz, 2025). At greater depths, water pressure tests indicate permeability values below 5 to 10 Lugeons.

According to Ewert (1992), permeability values below 5 Lugeons may be considered effectively impermeable. Similarly, Doig (1985) states that cement grouting is not feasible below 10 Lugeons, although chemical grouting may still be possible. In practical terms, this indicates that cement grouting carried out at permeability levels below 10 Lugeons does not provide any meaningful benefit.

Furthermore, given that the excavation-induced loosening zone beneath the dam foundation does not exceed approximately 15 m, there is no technical justification or benefit for applying consolidation grouting beyond this depth across the entire dam foundation. This conclusion is reinforced by the fact that measured Lugeon values are already below the cement grout take threshold. This approach is consistent with the recommendations for the Artvin Dam, which has a height of approximately 180 m, where consolidation grouting was advised to a depth of only 10 m in a 5 m × 5 m pattern (EİE, 1992). International practice at comparable dams likewise indicates that, by the mid-2000s, typical consolidation grouting depths were generally limited to approximately 15 m.

Similarly, for tunnels, it has been established that the excavation-induced loosening zone around the tunnel perimeter extends to no more than approximately half of the tunnel excavation diameter. As the tunnels at Yusufeli Dam are non-pressurized, consolidation grouting beyond half the excavation diameter would therefore provide no additional benefit.

The consolidation grouting carried out at Yusufeli Dam is illustrated in a video published by IC Consulting (2024). In this case, consistent with the foregoing analysis, grout intake per unit hole length indicates no effective grout take, with cement consumption largely confined to filling the drilled boreholes. This outcome is unsurprising, as the highly permeable upper 50 m of the foundation was already removed during foundation excavation. In the remaining rock mass, permeability values are below the 10-Lugeon threshold, rendering cement grouting ineffective.

Additionally, measurements from the Xiowan Dam indicate that the excavation-affected grouting zone extends to less than 15 m, further supporting this conclusion (Yilmaz, 2025). Accordingly, as demonstrated in the Artvin and Çine Dam projects, which benefited from the involvement of international designers, consolidation grouting lengths were intentionally limited to less than 15 m, in line with sound engineering practice.

Conclusion

The analysis demonstrates that the substantial cost escalation observed at the Yusufeli Dam was not the result of unavoidable technical conditions, but rather the cumulative outcome of unverified technical justifications, design-stage decisions, and construction-phase modifications. An unrealistically low concrete unit price at tender stage created a structural imbalance that necessitated compensatory measures before dam body concreting commenced. This imbalance was subsequently addressed through artificial reductions in foundation parameters, leading to inflated excavation volumes, extensive bedding concrete, and a disproportionate increase in high-cost prestressed anchoring works.

Despite authoritative and independent evidence contradicting the assumed ground conditions—including the approved final design documents, international studies, and data from nearby comparable dams—foundation characteristics were persistently portrayed as weaker than their actual state. This portrayal directly enabled a multiplicative increase in anchoring quantities and prices, culminating in anchoring costs alone reaching approximately USD 400 million, a figure exceeding the original tender value of the dam.

In parallel, spillway design decisions were driven by misinterpretation of test results, resulting in the cancellation of two originally planned gates and the construction of additional spillway tunnels at an estimated cost of USD 200 million, despite the existence of technically viable and less costly alternatives. Similarly, consolidation grouting quantities were expanded far beyond established engineering practice, without demonstrable technical necessity, further contributing to overall cost growth.

Taken together, these findings indicate a systematic pattern of project and cost modifications based on unverified or contradicted technical premises, rather than on sound engineering necessity or internationally accepted practice. From a forensic and engineering perspective, the resulting cost increases were largely foreseeable, avoidable, and disproportionate, underscoring the critical importance of rigorous verification of technical assumptions, transparent decision-making, and adherence to established design principles in large-scale dam projects.

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