# ENGINEERING DESIGN AND SAFETY ANALYSIS SUSTAINABILITY, RISK, AND CONSTRUCTION PRACTICES


*EDITOR*

*Assist. Prof. Dr. Serdar KASAP*

ASSIST. PROF. DR. ZEYNEB KILIÇ

ASSIST. PROF. DR. ÖZLEM ÖZKAN ÖNÜR

DR. JASİR MUSHTAQ

SEMA KARAHAN

ŞÜHEDA GÖKDAŞ



ISBN : 978-625-5753-75-5

Ankara - 2026

# ENGINEERING DESIGN AND SAFETY ANALYSIS: SUSTAINABILITY, RISK, AND CONSTRUCTION PRACTICES


**EDITOR**

Assist. Prof. Dr. Serdar KASAP

Bilecik Şeyh Edebali Üniversitesi

ORCID ID: 0000-0002-7847-3284

**AUTHORS**

Assist. Prof. Dr. Zeyneb KILIÇ[1]

Assist. Prof. Dr. Özlem ÖZKAN ÖNÜR[2]

Dr. Jasir MUSHTAQ[3]

Sema KARAHAN[4]

Şüheda GÖKDAŞ[5]

[1]Adıyaman University, Science Institute,
Civil Engineering Department, Adıyaman, Türkiye
**zkilic@adiyaman.edu.tr**
ORCID ID: 0000-0003-4954-6955

[2]İstanbul Nişantaşı University, Faculty of Engineering and Architecture,
Department of Architecture. İstanbul, Türkiye,
**ozlem.onur@nisantasi.edu.tr**
ORCID ID: 0000-0002-4110-4936

[3]Department of Civil Engineering, Government College of Engineering and Technology, Kashmir, 193501, Jammu and Kashmir, India
**drjasirnitsri@gmail.com**
ORCID ID: 0000-0003-4082-2108

[4]Adıyaman University, Science Institute,
Civil Engineering Department, Adıyaman, Türkiye
**semaakarahann@gmail.com**
ORCID ID: 0009-0002-0864-4233

[5]Adıyaman University, Science Institute,
Department of Civil Engineering, Adıyaman, Türkiye,
**251240106@adiyaman.edu.tr**
ORCID ID: 0009-0006-8334-0917

DOI: https://doi.org/10.5281/zenodo.19265322

(The Licence Number of Publicator: 2018/42945)

E mail: ubakyayinevi@gmail.com
www.ubakyayinevi.org
It is responsibility of the author to abide by the publishing ethics rules.


**ISBN: 978-625-5753-75-5**
March / 2026
Ankara / Turkey

## PREFACE

The challenges posed by climate change, rapid urban development, and increasing infrastructure demands require civil engineering practices to incorporate sustainability, safety, and advanced technological approaches. Within this framework, this book presents three interrelated studies focusing on key aspects of modern infrastructure.

The first chapter discusses the ecological significance of nature-based approaches in sustainable dam design, underlining the importance of harmony between engineering solutions and natural systems. The second chapter addresses dam safety through numerical modeling, including inspection procedures, analytical calculations, and spillway assessments, which are crucial for evaluating structural performance and minimizing risks. The third chapter focuses on stone façade cladding applications, highlighting material selection, on-site implementation principles, conformity assessment, and preventive measures against potential failures.

Overall, these chapters offer a combined perspective on sustainable design, structural safety, and material applications. This book aims to contribute to the literature while providing guidance for researchers and practitioners working toward safer and more sustainable engineering solutions.

**28.03.2026**

Assist. Prof. Dr. Serdar KASAP

**EDITOR**

**TABLE OF CONTENTS**

# CHAPTER 1
# THE ECOLOGICAL IMPORTANCE OF NATURE-BASED PRACTICES IN SUSTAINABLE DAM DESIGN

Sema KARAHAN
Assist. Prof. Dr. Zeyneb KILIÇ

## INTRODUCTION

Despite the many benefits provided of dams; such as energy generation, agricultural irrigation, flood control, and the provision of drinking water and so on; these engineering structures can also have negative effects on ecological and biological systems. In dam design, greater emphasis has often been placed on technical and economic criteria, while ecosystem health, biological diversity, and environmental sustainability are frequently treated as secondary considerations. When ecological factors are not adequately taken into account during the construction of hydroelectric dams, they can lead to habitat loss for living organisms, and particularly threaten the lives of aquatic species. Unsuitably managed flow regimes that do not consider ecological requirements disrupt aquatic ecosystems and damage the services provided by these ecosystems (including fish spawning cycles, passage routes for aquatic organisms, the use of water by living beings, nutrient cycling, productivity, and wildlife…). This situtiation, poses a serious risk to ecological balance and biodiversity. In recent years, as the negative impacts of climate change have become more pronounced and biodiversity loss has accelerated; so it has become necessary to place sustainability at the forefront in water infrastructure projects. In this context, nature-based solution methods offer a new paradigm in dam design by enabling approaches that consider ecological balance, remain sustainable, and are compatible with the environment. Water is an indispensable basic natural resource for human life, ecosystem health, and economic development (Kılıç, 2020). In recent years, to meet the increasing water demand of people, a large number of water structures have been constructed over aquatic ecosystems. Water structures affect conditions such as water clarity, water quality, water quantity, the temperature of the water, and biological diversity, and they also cause changes in river ecosystems and flow. When designing these big structures, it should not be forgotten that the living conditions of organisms and their habitats must not be harmed. If this is not sufficiently considered, the life cycles and migrations of aquatic species are adversely affected, and for many other organisms in the surrounding environment, threats to survival may emerge. In addition, hydrofit (aquatic) vegetation in rivers is also negatively impacted by changes in water quantity and water quality. The adverse effects on aquatic plants lead to habitat and food loss for the organisms that depend on them.

According to the United Nations' World Water Development Report in 2018, the concept of "Solutions for Nature" was emphasized, and within this scope a new trend emerged in the management of regional water resources. This concept is important for the sustainability of integrated water resources management (Hahn and

Kühnen, 2013). Nature-based approaches can be applied to many areas, including dam design, urban flood control, water security, ecosystem protection, and climate change adaptation. Therefore, nature-based solutions offer a reliable pathway for promoting sustainable economic development without causing harm to ecology and the environment. Sustainability is the approach that meets today's needs while preventing the depletion of natural resources and the disruption of environmental balance, thereby safeguarding future generations' right to meet their own needs. In practice, there is a lack of information and awareness about what and how nature-based solution studies can be implemented. In addition, it is not clear which quantitative criteria can be used to evaluate the implementation performance of nature-based solutions. Nature-based solutions are approaches developed against environmental problems and shaped by natural processes and structures; they provide multifaceted benefits for ecosystems, communities, and economies. These solutions contribute to sustainable development by supporting climate change mitigation and adaptation strategies (Boelee et al., 2017).

Ecosystems include both living (biotic) and non-living (abiotic) environments. Not harming the ecosystem and the nature that is a part of it is the most effective insurance policy for the lives of all living beings. Considering ecological conditions, and particularly biological diversity, it is crucial that nature-based solutions are not neglected in the design of dams and cities, for the benefit of all living organisms and especially for us. Nature-based solutions are advantageous approaches used to provide solutions to issues such as strengthening ecosystem and climate resilience and protecting biodiversity (Feyen et al., 2020).

Integrated water resources management, refers to the activities that involve the planning, organization, and control of water systems in a sustainable manner—responding to the views, expectations, and goals of all stakeholders. In this definition, since all sectors related to water are taken into account, the concepts of "social cohesion" and "ecological integrity" are also included, because water systems are addressed in an integrated way, and management responsibility is shared by every stakeholder. In modern dam design, the integration of nature-based solutions to ensure that biodiversity is not harmed has become one of the most critical issues in environmental engineering and hydraulic structure design today. The environmental impacts of dams have been discussed for many years. Planning dams by taking into account their impacts on ecosystems, biodiversity, and socio-economic and cultural pressures is of great importance for protecting natural resources and securing the future of humanity and other living beings. In this context, sustainable dam design approaches aim to offer solutions that protect not only the structure's technical functionality but also the ecological balance (Grigg, 2024). The integration of nature-based solutions into dam design provides many advantages. Applying nature-based approaches in dam projects includes a wide range of strategies such as creating ecological corridors for fish passage, installing natural filtration systems to improve water quality, and protecting local biodiversity. Dams should be designed in a way that does not force or endanger the living conditions of organisms in the surrounding area, does not cause habitat loss, preserves ecological balance, and remains sustainable—while costs should be determined accordingly. In Turkey, the adoption of sustainability principles in dam design is becoming increasingly important. Growing awareness of the impacts of hydropower plants on river ecology is leading engineers and decision-makers to search for more environmentally friendly alternatives. Nature-based practices contribute to more livable environments for future generations by providing long-term benefits in both ecological sustainability and economic efficiency (Nehren et al., 2025).

In this study, the fundamental principles of sustainable dam design are addressed, along with the application areas of nature-based solutions, ecosystem-based approaches, climate adaptation in water management, and multi-dimensional components such as interaction with local communities. In addition, the necessity and importance of integrating into planning and design processes the holistic structure of the ecosystem, the continuity of ecological processes, and the principles of biodiversity conservation, particularly in relation to hydraulic structures, and especially dams - are discussed. The primary aim of this study is to contribute to the literature by promoting the adoption of ecology- and biodiversity-based design approaches in water resources engineering practices, to raise awareness among stakeholders, and to provide a scientific basis for improving existing implementation practices.

## CONSIDERING ECOLOGICAL COMPONENTS IN DAM CONSTRUCTION

For all living beings to maintain healthy life processes, they need the benefits provided by ecosystems. Therefore, protecting ecosystem components and restoring those that are harmed in order to use natural resources sustainably is important for ensuring the continuity of ecosystem services. Nature-based solutions can strengthen ecosystem functioning and also help eliminate societal challenges that hinder sustainable development. The construction of dams and weirs has globally divided many rivers and streams into segments, posing a major threat to biodiversity. In dam-related structures, ensuring safe habitats for organisms in and around the water, protecting elements of the power plant structure, and preserving ecological balance are highly important from an environmental perspective (Seddon et al., 2019).

Within the scope of ecological and sustainable dam design, designers must first determine the ecological conditions of the region and the characteristics of biological diversity, and then shape their designs and planning accordingly. Dam construction is a process that leads to the formation of a completely new ecological system in river ecosystems (Baxter, 1977). Flow is the main driving force behind freshwater ecosystems; it is responsible for the distribution and function of the biota, as well as for geo-hydrological structure, and the transfer of matter and energy, and overall system efficiency (Poff et al., 1997). The effects of dam construction on biodiversity are multifaceted. The loss of native species, particularly sensitive endemic species, is closely related to the interruption of longitudinal and lateral connectivity between the river and floodplain, as well as changes in flow regime (Sarkar and Islam, 2020). According to the World Commission on Dams (2000) report, dam construction is a principal factor causing physical deterioration, fragmentation, and redirection of aquatic and terrestrial watershed ecosystems. In reservoirs, biodiversity, food resources, shelters, and habitats are abundant; however, fluctuations in water level create "dead zones" along the shoreline, causing stress on fauna and flora (Agostinho et al., 2008). In reservoirs, sedimentation reduces the availability of nutrients in downstream waters, thereby lowering the productivity of floodplains (Fred, 2006).

In addition, sediment-deprived water accelerates riverbank erosion and disrupts the delta formation process. Dams and diversions pose threats to freshwater fish and biodiversity, including the loss of species and the restructuring of communities, and often lead to taxonomic homogenization over time (Van et al., 2018). For these and similar reasons, ecological assessments must be carried out comprehensively in dam design processes. Designers should analyze all ecological components in detailed, such as riparian vegetation, aquatic macrophytes, fish populations, birds, and mammal species, and integrate this information into design decisions. For ecologically sustainable dam design, it is recommended that: the dam site be surrounded by forests in a way that allows the dispersal of mammal species; in the operational phase, intervention be kept to a minimum to permit habitat stabilization; suitable areas and ecological connections within canals near the dam be designed to easily meet mammals' vital needs, especially movement, feeding, and drinking; and environmental flow releases that mimic natural flow patterns be planned. Ultimately, adopting an ecosystem-based approach in dam construction plays a critical role in balancing both water resources management objectives and biodiversity conservation goals.

Dam impacts on fish include blocking migration routes, habitat fragmentation, the transformation from flowing water to still water in the dam area, the release of cold water from the reservoir hypolimnion, and changes in downstream flow regimes (Wu et al., 2019). Fish passages are hydraulic structures built in rivers where natural migration of fish is hindered by natural or man-made barriers, allowing fish to migrate toward upstream and downstream. Fish passages are classified according to the arrangement of in-channel structures (Katopodis, 1992). These include pool-type fish passes, denil-type fish passes, vertical-slot fish passes, and culvert-type fish passes. Pool-type fish passes are the oldest and most widely used, generally constructed for fish species with strong swimming abilities (Larinier, 2002). Denil-type fish passes consist of a rectangular trough with a series of closely spaced baffles along the bottom and sides. These baffles redirect part of the flow backward, reducing flow velocity and dissipating energy through spiral currents. As water velocity decreases, fish must move upward (Larinier, 2002). Vertical-slot fish passes consist of partitions/perforated plates placed at regular intervals along the passage length to direct flow and form a sequence of pools (Clay, 1995). On these partitions there is a narrow vertical slot extending from the bottom to the top. These slots enable fish to swim against the current without jumping over the obstacle, and also help balance water level variations created across the partitions. When a culvert is necessary for fish passage, then culvert-type fish passages are required. For culvert-type fish passes, culverts are generally placed in the lower part of streambeds (Katopodis, 1992).

There are also various versions of fish passages used in many countries; examples include fish lifts (fish elevators), rocky fish ramps, lock-type fish passes, trap-type fish passes, and eel passes. Today, although many hydraulic structures are built to meet the increasing demand for energy and water, these structures often restrict the upstream and downstream movements of aquatic organisms. A method to allow aquatic species to overcome these barriers and restrictions is to construct passages on top of the hydraulic structures. These passages are extremely important for aquatic organisms to sustain migration and reproduction. Therefore, fish passages and similar systems should be emphasized so that ecological damage to aquatic ecosystems can be minimized.

Köse (2021) states that, for the design of fish passages, habitat studies should first be carried out on the river where the hydropower plant is planned; based on these studies, fish species should be identified and a fish passage type suitable for those species should be selected. Baydar (2014) notes that due to the lack of habitat studies, migratory fish species cannot be determined; for fish passages to work effectively, habitat and biodiversity studies should be conducted first at the locations where the hydropower plant will be constructed. Kadıoğlu (2010) argues that the most important factor in designing fish passages is determining the target fish species; he also emphasizes that flow velocities must be carefully considered for the passage to function properly. In his study, Sorgucu (2016) suggests that when selecting materials to be used in fish passage construction, choosing materials similar to the natural structure around the site improves the passage's compatibility with nature. He also highlights the importance of greening/vegetation works in the fish passage area, consistent with the region's vegetation. Fish movement in natural river systems is affected by human-made structures, including dams and weirs. Therefore, especially regarding the negative effects of dam structures on fish populations, fish passage planning or measures to protect the natural balance of fish life are necessary (Chanson and Gonzalez, 2024; Grimardias et al., 2022).

It is necessary to identify fish species living in the region, select the fish passage type that can perform most efficiently, and monitor operational processes. Regular maintenance and cleaning of fish passages, as well as releasing a sufficient amount of water suitable for the habitat, will ensure continuity of aquatic life. Fish passages should be planned to enable fish to move not only from upstream to downstream but also from downstream to upstream. This helps protect fish populations, especially during the spawning season. Covering fish passages with grates is required for safety, as it protects fish during passage from bird species. To protect fish populations, fishing activities should be prohibited in the area where the regulator and fish passage are located. Cracks that may occur in the side walls can cause water loss and hinder the passage's operation. Because the minimum "environmental flow" released from regulators will be directed into the fish passages, turbulence should not be allowed at the outlet of the passage; structures should be built to break and dissipate the energy of the water. In regulators without fish passages, the continuity of aquatic life should be ensured through trapping and transport methods (O'Connor et al., 2022; Knott et al., 2023).

In this context, ecological approaches should be adopted in dam design, including arrangements that will not constrain habitat conditions for living organisms and will support migration movements of species—especially fish and aquatic insects. The integration of nature-based solutions in sustainable dam designs is presented as an indispensable requirement for both meeting energy needs and preserving ecological balance.

## CONCLUSION AND RECOMMENDATIONS

In sustainable dam design, the integration of nature-based practices is of critical importance for preserving ecological integrity beyond traditional engineering approaches. Implementations such as fish passages, ecological corridor arrangements, sediment management systems, and restoration of native vegetation can significantly reduce the negative impacts of dams on aquatic ecosystems and support the continuity of biodiversity. Through these approaches, the natural processes of river and reservoir lake ecosystems can largely be preserved, especially the habitats of sensitive endemic species can be secured, and water quality can be improved. Moreover, considering the effects of climate change on water resources, nature-based solutions help strengthen ecosystem resilience to climate and thus ensure long-term sustainability. Establishing a balance between hydropower generation and ecological protection is not only an environmental necessity, but also a fundamental requirement for leaving a livable world to future generations. Therefore, making nature-based practices a standard approach in all processes—from the planning stage to operation—in dam projects is essential for achieving sustainable development goals.

The negative impacts that hydropower plants (HPPs) can create on biodiversity and the environment during their construction and operation phases should not outweigh the benefit of energy production. Hydrological structures should be designed in a way that considers, protects, and ensures the sustainability of both aquatic and terrestrial environments. Sustainable dam design is not only a technical approach, but also an ecological, social, and governance-oriented one; when applied together with nature-based solutions, dam projects can become more flexible and resilient, more compatible with the environment, and can minimize harm to the biodiversity in and around them. In future dam designs, it is of great importance that such multidimensional, eco-friendly approaches become standard practice.

## REFERENCES


Kılıç, Z. (2020). The importance of water and conscious use of water. *International Journal of Hydrology,* 4, 239–241.

Schilt, C.R. (2007). Developing Fish Passage and Protection at Hydropower Dams. *Applied Animal Behaviour Science,* 104, 295-325.

Hahn, R., & Kühnen, M. (2013). Determinants of sustainability reporting: a review of results, trends, theory, and opportunities in an expanding field of research. *Journal Clean Product,* 59, 5-21.

Boelee, E., Jan, Janse., Antoine Le, G., Marcel, K., Rob, Al., Willem, L. (2017). Overcoming water challenges through nature-based solutions. *Water Policy,* 19(5), 820-836.

Feyen, L., Ciscar, M., Carlos, J., Simon, G., Ruiz Dolores, I., Ramirez A.S., Alessandro, D., Gustavo, N., Simone, S., Giuseppe, F., Giovanni, Girardello, M., Spinoni, J., Mentaschi, L., & Bisselink, B., (2020). Climate change impacts and adaptation in Europe. *JRC PESETA IV final report, JRC Research Reports* JRC119178, Joint Research Centre.

Neil, S.G. (2024). Framework and Function of Integrated Water Resources Management in Support of Sustainable Development. *Sustainability,* 16(13), 5441.

Nehren, U., Barrett, A.C., Quiros, P.S., Fekete, A. (2025). Integrating Nature-Based Solutions (NbS) for Enhanced Flood Resilience under a Changing Climate: The Case of the Cologne District, Germany. https://doi.org/10.5194/egusphere-2025-4888.

Nathalie, S., Beth, T., Pam, B., Alexandre, C., & Cécile, A. J. G. (2019). Grounding nature-based climate solutions in sound biodiversity science. *Nature Climate Change,* 9, 84-87.

Baxter, R.M. (1977). Environmental effects of dams and impoundments. *Annual Review of Ecology and Systematics,* 8 (1), 255-283.

Poff, N. L., Allan, J. D., & Bain, M. B. (1997). The natural flow regime: A paradigm for river conservation and restoration. *BioScience,* 47(11), 769-784.

Sarkar, U. K., & Islam, M.S. (2020). River connectivity and fish diversity in tropical rivers: Implications for conservation. *Marine and Freshwater Ecosystems,* 30(8), 1534-1546.

World Commission on Dams (2000). Dams and Development: A New Framework for Decision-Making. *Earthscan Publications,* London

Agostinho, A.A., Pelicice, F.M., & Gomes, L.C. (2008). Dams and the fish fauna of the Neotropical region: impacts and management related to diversity and fisheries. *Brazilian Journal of Biology,* 68 (4), 1119-1132.

Fred, P. (2006). Downstream ecological effects of dams: A geomorphic perspective. *BioScience,* 56 (3), 183-192.

Van, T.C. (2018). Effects of dam construction on sediment budget and channel morphology. *Hydrological Processes,* 32 (15), 2416-2428.

Wu, J., Cheng, S., & Li, Z., (2019). Effects of dam construction on biodiversity: A review. *Journal of Cleaner Production,* 221, 480-489.

Katopodis, C. (1992). Introduction to fishway design. Freshwater Institute, Central and Arctic Region, Department of Fisheries and Ocean. *Working Document,* 70p

Larinier, M. (2002). Fishways–General considerations. Bulletin Francais De La Peche Et De La. *Pisciculture,* 364, 21–27.

Clay, C.H. (1995). Design of Fishways and Other Fish Facilities. Department of Fisheries of Canada, Ottowa. https://doi.org/10.1201/9781315141046

Köse, A.E. (2021). Hidroelektrik Santrallerde Balık Geçitleri Sorunları: Gümüşhane ve Bayburt Örneği. *Yüksek Lisans Tezi,* Gümüşhane Üniversitesi, Gümüşhane, Türkiye.

Baydar, Ş. (2014). Doğu Akdeniz Bölgesindeki balık geçit sistemlerinin yapısal özelliklerinin belirlenmesi. *Yüksek Lisans Tezi.* Kahramanmaraş Sütçü İmam Ünv, Kahramanmaraş, Türkiye.

Kadıoğlu, C. (2010). Balık geçitlerinin sayısal analiz ile modellenmesi. *Yüksek Lisans Tezi,* İstanbul Teknik Üniversitesi, İstanbul, Türkiye.

Sorgucu, O. (2016). Balık geçitlerinin hidrolik açıdan değerlendirilmesi. *Yüksek Lisans Tezi,* Erciyes Üniversitesi, Kayseri, Türkiye.

Chanson, H. & Gonzalez, C. (2024). Downstream fish passage on dam spillway: Low fish mortality rate at Paradise Dam stepped spillway. *Ecological Engineering,* 204, 107267.

Grimardias, D., Chasserieau, C., Beaufils, M. & Cattan´eo, F. (2022). Ecological connectivity of the upper Rhˆone River: Upstream fish passage at two successive large hydroelectric dams for partially migratory species. *Ecological Engineering,* 178, 106545.

O'Connor, J., Hale, R., Cooper, M. M., Cooke, S.J. & Stuart, I. (2022). Developing performance standards in fish passage: Integrating ecology, engineering and socio-economics. *Ecological Engineering,* 182, 106732.

Knott, J., Mueller, M., Pander, J. & Geist, J. (2023). Bigger than expected: Species and size-specific passage of fish through hydropower screens. *Ecological Engineering,* 188, 106883.

# CHAPTER 2

# DAM SAFETY ANALYSIS WITH NUMERICAL MODELING: INSPECTION, CALCULATION AND SPILLWAY INVESTIGATIONS

Şüheda GÖKDAŞ
Dr. Öğretim Üyesi Zeyneb KILIÇ
Dr. Jasir Mushtaq

## INTRODUCTION

Water is a fundamental natural resource essential for human survival, ecosystem health, and economic development (Kılıç, 2020). With the increase in population and the development of industry, the need for water and energy has increased. Dams are important engineering structures that play a role in water supply, energy generation, flood control, irrigation, and the sustainable development of societies. However, due to engineering problems and deficiencies in dams, the risk of collapse may arise. Therefore, it is important to identify these deficiencies and take preventive measures. It is also necessary to determine the reliability levels of existing dams and carry out appropriate risk and safety assessments (Kılıç and Emiroğlu, 2009).

Through the risk and safety assessments conducted on existing dams, efforts are made to determine their current condition, safety levels, and any deficiencies. This enables preparedness against potential dam-related hazards and highlights the need for rehabilitation where necessary. Such studies on existing dams serve as a valuable source of information and experience for future dam constructions, allowing for the reduction or complete elimination of similar risks that may arise. From the first day of construction, dams are subjected to various loads. Understanding their behavior under these loads in advance and continuously monitoring them, are crucial for identifying potential deficiencies before they evolve into disasters. Taking necessary precautions beforehand is vital to prevent such deficiencies from turning into catastrophic failures. Therefore, dams should be designed considering all possible load conditions they may face, monitored continuously using accepted measurement techniques during construction and operation phases, benefit from technological advancements and numerical modeling processes, be inspected periodically, and have action plans prepared and strictly followed during emergencies. Moreover, issues such as climate change, global warming, and other ecological factors can lead to hydrological changes in the regions where dams are constructed. Thus, proper dam design, operation, monitoring of their behavior under varying impacts, and risk level assessments are of great importance. Otherwise, dam failures may inevitably lead to significant loss of life and property (Yenigün, 2007; Ağıralioğlu, et al., 2018). Dam statistics show that the most frequently damaged dams are embankment dams, followed by gravity dams, rockfill dams, and arch dams, respectively. The most critical failure mode in embankment dams is the progressive development of internal erosion due to seepage, which can eventually lead to the formation of a breach on the downstream face. In concrete dams, the most significant problem is the formation of cracks, which compromises shear stress resistance and thereby endangers the structural safety of the dam (Liu, et al., 2024).

The deficiencies observed in dams that put dam safety at risk are as follows: Foundation deficiencies; irregular settlements and sliding of the foundation soil. Inadequacies arising from natural construction materials. Seepage related deficiencies: water leak through the dam body (piping) and under the foundation. Overtopping-related deficiencies. Inadequacies caused by water overtopping the dam due to spillway insufficiency. Structural deficiencies resulting from seismic events. Crack-related deficiencies; longitudinal cracks, transverse cracks, and shrinkage-drying cracks. Slide-related deficiencies; slips occurring in the dam body due to high pore water pressure and landslides on reservoir banks. Structural deficiencies; due to depressions or settlements in the dam body. Operational and calculation errors. Deficiencies caused by operation mistakes or incorrect design calculations (National Academies of Science, 1983).

Dam safety is directly affected by factors such as the aforementioned deficiencies, seepage in the dam body with foundation, slope stability, and spillway behavior. Numerical modeling methods have become increasingly important in recent years in identifying and analyzing these processes. Furthermore, not only classical engineering approaches but also Numerical Modeling and Risk-Based Analysis Methods have been widely used in the design, operation, and maintenance processes of dams. As part of the "Dam Safety Monitoring Program" conducted by the State Hydraulic Works (DSI), monitoring the physical and hydraulic behavior of dams and conducting periodic assessments of risky structures is mandatory. However, due to limited field measurements, the complexity of load changes over time, and varying soil conditions, classical calculation methods are often inadequate. In this regard, numerical modeling methods are increasingly being used in engineering decision-making processes. Numerical modeling is based on simulating the behavior of complex engineering systems using mathematical equations. In dam engineering, these models can analyze water movement in the dam body with foundation, material deformations, slope stability, and flood flows. The most widely used software in this field include HEC-RAS, CFD (Computational Fluid Dynamics) based tools (e.g. FLOW-3D, ANSYS Fluent) and finite element-based geotechnical modeling programs such as PLAXIS (Pilotti, et al., 2020).

In dam safety studies, three fundamental components come to the forefront: Seepage Analysis: Determines the movement of water through the dam body and foundation. *Slope Stability:* Assesses soil behavior and calculates the safety factor of the dam slopes. *Spillway and Hydraulic Structure Analyses:* Evaluates flood passage, cavitation risk, air entrainment, and energy dissipation behavior (Heitland and Donaghy, 2021). These three components are closely interconnected. For example, increased seepage pressures can directly reduce slope stability, while an inadequate spillway capacity can lead to overtopping and severe dam body damage. Therefore, multi-model approaches are preferred in dam safety assessments (for instance, using a combination of HEC-RAS+PLAXIS+CFD tools) to evaluate hydraulic, geotechnical, and structural behaviors together.

In this study, dam safety research conducted using HEC-RAS, PLAXIS, and CFD-based approaches was examined through literature-based review. The findings indicate that evaluating dam safety using multi-model approaches and risk-based analyses yields more reliable results. Moreover, the combined use of experimental and numerical analyses provides the most dependable outcomes for ensuring dam safety.

## NUMERICAL MODELING APPROACHES

Numerical modeling methods used in dam safety analyses aim to represent different physical processes such as water flow characteristics, soil behavior, and structural strength. Therefore, it is challenging for a single modeling tool to accurately capture all these behaviors simultaneously. Three most commonly used methods in the literature are hydraulic flow modeling (HEC-RAS), computational fluid dynamics analysis (CFD), and geotechnical modeling (PLAXIS) approaches.

**HEC-RAS Based Hydraulic Modeling**

HEC-RAS (Hydrologic Engineering Center - River Analysis System) is a hydraulic software used to calculate water surface profiles for one-dimensional steady flows and to model unsteady flows, with capabilities for data storage and management. The software can perform both 1-dimensional (1D) and 2-dimensional (2D) flow calculations. It is especially preferred for processes such as dam break analysis and flood wave propagation.

HEC-RAS is based on the numerical solution of the continuity and momentum equations, known as the Saint-Venant equations. These equations represent the depth-averaged form of mass and momentum conservation.

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} = 0$$

$$\frac{\partial (uh)}{\partial t} + \frac{\partial (u^2 h)}{\partial x} + gh\frac{\partial h}{\partial x} = gh(S_0 - S_f)$$

Here, $h$ is water height, $u$ is average flow rate, $S_0$ is base slope, and $S_f$ is friction slope.

HEC-RAS software is widely preferred for modeling dam failure scenarios and provides successful results in simulating flood wave propagation in the downstream region (Butt, et al., 2013; Haltaş, et al., 2016; Azeez, et al., 2020). The most important advantages of

HEC-RAS models are their user-friendly interface, ease of GIS-based data entry, and ability to produce reasonably accurate results over large-scale areas. However, the software is limited by its inability to represent micro-scale turbulence models and its neglect of 3D flow effects. Therefore, it is recommended to supplement spillway and energy dissipation structure analyses with CFD models.

**CFD (Computational Fluid Dynamics)**

CFD (Computational Fluid Dynamics) is a numerical modeling method that solves fluid behavior in three dimensions using the Navier–Stokes equations. CFD models provide high-resolution results in the analysis of complex flow phenomena such as spillways, energy dissipators, air mixing, and cavitation.

The basic form of the Navier–Stokes equations is as follows:

$$\rho(\frac{\partial \mathrm{u}}{\partial t} + \mathrm{u} \cdot \nabla \mathrm{u}) = -\nabla p + \mu \nabla^2 \mathrm{u} + \rho \mathrm{g}$$

Here $\rho$ is density, $\mu$ is dynamic viscosity, u is velocity vector, $p$ is pressure, and g is gravitational acceleration.

Among CFD software, FLOW-3D, ANSYS Fluent, and OpenFOAM are the most widely used. In dam failure problems, CFD models can simulate complex hydrodynamic behavior and shock wave interactions, especially in the initial stages of flow, with high accuracy (Ozmen-Cagatay and Kocaman, 2010; Ozmen-Cagatay and Kocaman, 2011; Kocaman and Ozmen-Cagatay, 2015; LaRocque, et al., 2013a;

LaRocque, et al., 2013b; Esmaeeli Mohsenabadi, et al., 2023). Although limited studies CFD-based spillway analyses in Türkiye; these kind of researches have been increasing in recent years:

The Köprü Dam spillway flow was investigated with both physical model (1/60 scale) and numerical model (FLOW-3D). FLOW-3D (RANS, RNG, k-ε, k-ω models) were used. Experimental and CFD results were compared. The difference ratio was found to be between 1.17% and 2.60% (Kumcu and Uçar, 2020).

The performance of aerator structures of Ilısu Dam was examined with ANSYS Fluent; the effect of air mixing ratios on the flow regime was analyzed (Aydın and Kaplan, 2019).

The advantage of CFD models in dam failure analyses is their ability to examine in detail the velocity distributions, pressure changes, and turbulence structures in the flow field (Ozmen-Cagatay ve Kocaman, 2010). CFD models provide predictions consistent with experimental results, particularly in determining the shock waves and hydrodynamic loads generated when flow impinges on wall structures (Kocaman and Ozmen-Cagatay, 2015). However, the high computational cost and calibration requirements make these models difficult to use in large-scale risk analyses.

**PLAXIS and Slope/Seepage Analyses**

The stability of dam bodies is directly related to the underlying soil properties. PLAXIS software analyzes soil deformations, stress distributions, and seepage behavior using the finite element method (FEM).

The fundamental equations used in PLAXIS are a combination of groundwater flow equations based on Darcy's law and elastoplastic soil behavior models.

$$q = -k\frac{dh}{dl}$$

The equation defines the flow of water per unit area ($q$), the permeability coefficient ($k$), and the hydraulic head difference (*dh/dl*).

El-Hazek et al. (2020) used PLAXIS models to define four different soil types (sand, silt, etc.). For each soil, water infiltration and the coefficient of safety (FS) were calculated by varying the hydraulic conductivity (k). Numerical results were also compared with laboratory experiments (model dam). The results showed that as permeability increases, the amount of infiltration increases, affecting the safety (FS) of the slope in different soil types (El-Hazek, vd., 2020).

PLXIS models provide reliable results, particularly in examining the infiltration-slope relationship. However, they cannot directly model the hydraulic components of dam safety (e.g., flood flow rates), so they are generally evaluated in conjunction with HEC-RAS or CFD results.

## EXPERIMENTAL–NUMERICAL COMPARISONS AND MODEL VALIDATION

In dam safety studies, comparison with experimental (laboratory or field) data is essential to assess the validity of numerical model results. Model validation and calibration are the most important steps to increase the reliability of simulation results. Literature reviews have revealed a high correlation between numerical and experimental results, particularly in spillway flows, flood wave propagation, and seepage analyses. Comparisons of experimental studies and numerical modeling results in dam failure problems have shown that CFD approaches can predict water surface profiles, velocity distributions, and wave propagation mechanisms with high accuracy (Ozmen-Cagatay and Kocaman, 2011; LaRocque, et al., 2013a).

Some research examples from Turkey and around the world are presented as; in the Köprü Dam example, the behavior of the spillway structure was modeled with FLOW-3D software and compared with the results of a physical model performed at the DSI Hydraulics Laboratory. 1–3% difference was found between the experimental and CFD data; a cavitation risk was also identified at flow velocities of 25 m/s. These results demonstrated that the CFD model showed high agreement with the physical data and that network resolution was a determining factor in accuracy (Kumcu and Uçar, 2020).

The Batman Dam failure analysis was conducted using the HEC-RAS 2D model; in this study, a complete failure scenario created using the Froehlich (2008) approach was modeled for the downstream region, and the obtained results were compared with DSI flow monitoring station data to ensure calibration. Model outputs showed that the maximum flood depth reached approximately 35 m, and flow velocities reached 8 m/s in some places. The failure duration was determined to be 3.9 hours. The difference between actual measurements and model results was minimal, demonstrating the high accuracy of the HEC-RAS 2D model in dam failure analyses. It was also noted that grid resolution has a significant impact on accuracy, and that modeling with a 5 m mesh resolution yielded more consistent results than the 10 m resolution model (Efe and Önen, 2022).

In a study conducted for the Ilısu Dam (2019), the performance of the aerator structures was modeled with ANSYS Fluent and compared with field measurements. CFD analyses performed with ANSYS Fluent found average air concentrations in the 2010 revised design range of 8–23%, exceeding the 6–8% limit required for cavitation protection. These validation results demonstrate that CFD models can accurately represent both air-water interactions and energy dissipation mechanisms in dam spillway structures (Aydın and Kaplan, 2019).

El-Hazek et al. (2020) compared infiltration rates for different soil types both in laboratory settings and with the PLAXIS model. Good agreement was demonstrated between the model and experimental data (El-Hazek, et al., 2020).

Nikrou & Pirboudaghi (2024) modeled cavitation behavior in free-flowing curvilinear spillways using CFD and reported that the numerical findings were in high agreement with experimental observations (Nikrou and Pirboudaghi, 2024).

In experimental and numerical studies of two-dimensional dam break flows, it was determined that both shallow water equations (SWE) and RANS-based approaches successfully captured the flow characteristics, but the RANS approach provided more accurate results in complex flow regions requiring turbulence modeling (Ozmen-Cagatay and Kocaman, 2010; LaRocque, et al., 2013a). The use of three-dimensional LES and k-ε turbulence models, particularly in partial dam break scenarios, allowed for more detailed analysis of flow structures and velocity profiles (LaRocque, et al., 2013b). These results demonstrate that modern numerical modeling approaches, when applied with accurate boundary conditions and appropriate calibration, can yield results that closely approximate physical reality.

While experimental validation opportunities are limited in dam projects in Türkiye, existing studies (Batman, Köprü, Ilısu) demonstrate the reliability of numerical models (Kumcu and Uçar, 2020; Aydın and Kaplan, 2019; Efe and Önen, 2022). Hybrid approaches using HEC-RAS and CFD models together allow for the evaluation of flood propagation and spillway behavior within the same framework.

## RISK SCENARIOS AND DAM SAFETY ANALYSES

Dam safety should be evaluated not only under normal operating conditions but also under extraordinary circumstances. In this context, the risk scenario concept is an analytical approach aimed at predicting how the dam and its downstream area will be affected in the event of a potential failure or disaster. The most frequently studied risk types in the literature are dam failure, earthquake impact, gate failure, and extreme flood scenarios.

**Dam Failure Modeling**

Dam failure modeling is a complex process where both hydraulic and structural factors are evaluated together. HEC-RAS is one of the most widely used tools in this type of analysis.

In the study conducted on the Batman Dam example, three different failure scenarios were modeled: complete dam failure, partial dam failure, and spillway capacity insufficiency. The complete failure scenario of the Batman Dam was analyzed with the HEC-RAS 2D model; model results revealed flood depths of up to 35 m downstream and flow velocities reaching 8 m/s in some areas. These findings indicate that the dam failure scenario poses a high flood risk in the downstream area (Efe and Önen, 2022). Similarly, the flood wave resulting from the dam failure at Rahmanlar Dam, was examined using the HEC-RAS 1D model, and it was determined that the flood spread approximately 3.5 km downstream, affecting the villages of Üzümlü and Ortaköy (Kemaloğlu, et al., 2019).

International applications have also shown that the HEC-RAS 2D model can successfully simulate flood wave propagation and downstream impacts in dam failure scenarios and is an effective tool for generating risk maps when integrated with geographic information systems (Pilotti, et al., 2020; Haltaş, et al., 2016).

## Earthquake and Dynamic Loading Effects

Earthquake effects are a critical risk factor for slope stability, especially in embankment-type dams. Accelerations occurring in the dam during an earthquake alter both dynamic stress distributions and seepage paths. Experimental and numerical analyses conducted by El-Hazek et al. (2020) determined that dynamic loading under different soil types and earthquake accelerations reduces slope stability by increasing pore water pressure. The study reported that the factor of safety under dynamic conditions decreases to lower values compared to the static case (El-Hazek et al., 2020).

In a recent study conducted in Türkiye, two-dimensional flood modeling of dam failure caused by pipelines triggered by seismic deformation was conducted. In the case of the Doğantepe Dam, a scenario where internal erosion initiated by the earthquake could lead to dam failure was modeled with HEC-RAS; this study is important because it demonstrates that earthquake risk can not only affect structural stability but also trigger infiltration and internal erosion mechanisms, leading to a secondary collapse risk. Finite element software such as PLAXIS is frequently preferred in earthquake risk analyses because it can model soil deformation and pore water pressure changes over time in such dynamic analyses (Demir, et al., 2025).

## Gate Failures and Spillway Inadequacies

Gate failures in dams can cause sudden and uncontrolled water releases, leading to serious structural damage and life safety risks in both the spillway and downstream areas. Failures in the mechanical or hydraulic systems of gates, particularly during high-flow floods, directly threaten the operational safety of the dam. Literature indicates that spillway inadequacies cause up to 35% of dam failures (Yenigün, 2021). Therefore, regular maintenance and monitoring of gates, risk analyses, and rehabilitation efforts are critical.

In a study on Köprü Dam, the behavior of the spillway structure was modeled both physically and numerically using FLOW-3D software. It was determined that the average flow velocity reached 25 m/s, and the difference between CFD and experimental data was within 2%. This result demonstrates that CFD-based modeling provides high accuracy in assessing the performance of energy-dissipating structures (Kumcu and Uçar, 2020). Similarly, a study conducted at the Ilısu Dam reported that the spillway aerator design played a critical role in preventing cavitation damage, and the revised design was validated with CFD analyses (Aydın and Kaplan, 2019; Kaplan, 2018). Furthermore, Flow-3D analyses of stepped spillways revealed that the energy dissipation ratio could increase by up to 78% depending on the step geometry (Yalçın, et al., 2024; Dursun and Öztürk, 2009).

In recent years, CFD modeling has been widely used to solve complex hydraulic problems such as gate vibrations, cavitation risk, and energy-dissipating basin design. These methods offer both cost and time advantages compared to physical modeling and allow for rapid testing of different scenarios (Büyükbaş, et al., 2017).

## Climate Change and Extreme Flood Scenarios

Global climate change directly affects precipitation patterns and flood frequencies. Integrating climate change scenarios into dam safety studies has become a significant trend in the literature in recent years. In a study on Seyhan Dam (Adana-Türkiye), 100-, 200-, and 500-year flood scenarios were analyzed with the HEC-RAS 2D model. It was determined that under 500-year flood conditions, spillway capacity would reach limiting values and a risk of overflow at the dam crest level could occur (Çalışkan and Uğur, 2024).

Garsore et al. (2023) examined artificial intelligence methods used to predict seepage behavior in mass dams and emphasized that artificial neural networks (ANNs), adaptive neurofuzzy inference systems (ANFISs), and hybrid machine learning approaches, in particular, provide more reliable results compared to traditional empirical methods. The study also stated that expanding AI-based models to include hydro-climatological factors (e.g., temperature and precipitation changes) is critical for assessing dam safety under climate change conditions (Garsore, et al., 2023).

## Risk Management and Multi-Disciplinary Approaches

Today, dam safety analyses are based not only on engineering calculations but also on risk management and decision support systems. Risk analysis generally consists of three components:

*Probability;* likelihood of a failure occurring,

*Exposure;* sensitivity of the downstream population and infrastructure,

*Consequence;* potential economic, environmental, and life-threatening impacts.

A risk matrix, created by evaluating these elements together, determines the level of dam safety. Within the scope of the "Dam Safety Management System" project launched by the State Hydraulic Works (DSİ) in Türkiye in 2019, national risk maps are being produced by integrating HEC-RAS flood models with PLAXIS soil analyses. Analyzing dam failure flows in the presence of obstacles is critical to understanding the exposure of downstream structures and infrastructure to flood waves. Studies using both experimental and CFD simulations have shown that obstacles significantly affect water surface profiles and flow velocities, and that accurate modeling of shock wave reflection and refraction mechanisms is essential for risk assessments (Ozmen-Cagatay and Kocaman, 2011).

Two-dimensional numerical modeling of flood wave propagation from dam failures in urban areas is crucial for determining how structural density alters flow characteristics and which areas are at high risk. A study on the Ürkmez Dam showed that while building and road systems in the urban area slow flood propagation, they also increase water depth in some areas, creating local hazards (Haltaş, et al., 2016).

All these studies demonstrate that, the most effective approach in dam safety analyses is a multidisciplinary modeling strategy. Hydraulic, geotechnical, and structural components should be evaluated together, not separately.

HEC-RAS accurately represents flood and flood dynamics,

CFD accurately represents the complex three-dimensional behavior of flow,

PLAXIS accurately represents ground deformations.

Combining these three approaches across scenarios allows disaster management plans to be built on more realistic and reliable foundations.

## RESULT AND DISCUSSION

The literature review demonstrates that numerical modeling methods are increasingly being used in dam safety assessments and that these methods offer significant advantages over traditional engineering approaches.

HEC-RAS, CFD, and PLAXIS software are complementary tools in that they represent different physical processes. HEC-RAS can accurately model flood wave propagation over large areas, CFD can accurately model complex flow behavior in spillways and energy dissipation structures, and PLAXIS can accurately model ground deformation and seepage problems. However, each method has certain limitations. For these reasons, multi-model analysis approaches have become increasingly common in the literature in recent years. Local studies conducted on the Batman, Köprü, Ilısu, and Rahmanlar dams show that this integration increases accuracy rates to over 90% (Kumcu and Uçar, 2020; Aydın and Kaplan, 2019; Efe and Önen, 2022; Kemaloğlu, et al., 2019).

HEC-RAS models are inadequate for representing micro-scale turbulence and air-water interactions, while CFD models require high computational power and are costly for long-term or large-scale analyses. PLAXIS, on the other hand, cannot directly analyze hydraulic interactions and requires integration with other software.

Internationally, Nikrou & Pirboudaghi (2024) found that the CFD model provided a 95% correlation with laboratory data (Nikrou andPirboudaghi, 2024); El-Hazek et al. (2020) found that the PLAXIS model had an average error of 6% in slope stability analyses (El-Hazek, et al., 2020); and Garsore et al. (2023) demonstrated that AI-supported seepage prediction models can be used to supplement classical methods (Garsore, et al., 2023).

The importance of experimental verification in dam failure problems has been emphasized by studies demonstrating that rapid changes and complex turbulent structures in the initial stages of flow can only be verified through detailed measurements (Ozmen-Cagatay and Kocaman, 2010; Ozmen-Cagatay and Kocaman, 2011; Esmaeeli Mohsenabadi, et al., 2023). Comparison of shallow water equations (SWE) and RANS approaches, especially in the early stages of dam failure, has shown that both methods offer different advantages, but RANS models capture turbulence effects better (Ozmen-Cagatay and Kocaman, 2010). Investigating the interaction of flow with vertical walls and shock wave effects is critical for predicting structural damage in the downstream area. Modeling such interactions, both experimentally and numerically, provides reliable results in determining the hydrodynamic loads that may occur as a result of a dam failure (Kocaman and Ozmen-Cagatay, 2015).

Today, dam safety research focuses not only on engineering but also on decision support and risk management. Climate change, heavy rainfall, and increasing earthquake activity, in particular, indicate the need to move beyond classical design approaches. In this regard, numerical simulations have become an important tool in both engineering design and emergency planning. This literature review demonstrates that numerical modeling methods are versatile and effective tools in dam safety analyses.

The main results obtained can be summarized as follows: HEC-RAS produces fast, user-friendly, and reasonably accurate results in dam failure and flood analyses. It is particularly effective in creating wide-area flood maps thanks to its integration with geographic information systems (Pilotti, et al., 2020; Butt, et al., 2013; Haltaş, et al., 2016).

CFD models provide high-resolution results in spillway, energy dissipation, and cavitation analyses. Strong correlations with experimental data have been obtained in modeling the initial stages of dam break flows and in examining shock wave interactions (LaRocque, et al., 2013a; LaRocque, et al., 2013b; Esmaeeli Mohsenabadi, et al., 2023).

PLAXIS provides reliable results in soil-water interaction modeling and infiltration analyses. It is particularly preferred for earthquake and dynamic load analyses. The most reliable results were obtained when multi-model approaches (e.g., HEC-RAS + CFD + PLAXIS) were used. This combination allows for the assessment of all aspects of dam behavior. Literature demonstrates that AI-based modeling approaches can be used to supplement classical methods (Garsore, et al., 2023). These methods will play a significant role in real-time dam monitoring and early warning systems in the future.

Consequently, the integration of numerical modeling in dam safety analyses has become not only an academic requirement but also a practical engineering necessity. The experience of the Batman, Sürgü, Rahmanlar, and Köprü dams studies conducted in Türkiye parallels findings in the international literature, demonstrating that domestic modeling capacity has become globally competitive (Kumcu and Uçar, 2020; Aydın and Kaplan, 2019; Kemaloğlu, et al., 2019). It is recommended that future studies be supported by climate change scenarios, AI-supported forecasting models, and real-time monitoring systems.

Furthermore, detailed examination of dam failure flows in different geometric configurations (narrowing channels, obstructed zones, urban areas) will enable more comprehensive risk assessments (Ghaderi, et al., 2025). Numerical modeling of earthquake-induced internal erosion and pipeline mechanisms should also be a priority in future studies (Demir, et al., 2025). These approaches will enable a sustainable, dynamic, and scientifically based transformation in dam safety management. The literature reviewed in this study demonstrates that dam safety research in Türkiye complies with international standards. However, further work is needed on the integration of climate change scenarios and the development of artificial intelligence-supported early warning systems.

## REFERENCES


Kılıç, Z. (2020). The importance of water and conscious use of water. *International Journal of Hydrology,* 4(5), 239–241.

Kılıç, Z., & Emiroğlu, M.E. (2009). Kaya olmayan temeller üzerinde inşa edilen düşük yükseklikli ssb barajların statik analizi. *UA Baraj güvenliği sempozyumu,* Tam metin yayın.

Yenigün, K. (2007). Dolusavaklarda taşkına dayalı güvenilirlik ve BARAJ_RISK programıyla risk analizi uygulaması. *1. Ulusal Baraj Güvenliği Sempozyumu ve Sergisi,* (301-318). Ankara, Türkiye.

Ağıralioğlu, N., Altunkaynak, A., Özger, M., & Kartal, E. (2018). Baraj güvenliği uygulamaları: Göktürk Barajı örneği. *Uluslararası V. Baraj Güvenliği Sempozyumu* (1108-1118), İstanbul, Türkiye.

Liu, G., Zhou, Z., Zhang, J., Jiang, G., & Mi, W. (2024). Seepage and Stability Analysis of Earth Dams' Downstream Slopes, Considering Hysteresis in Soil–Water Characteristic Curves under Reservoir Water Level Fluctuations. *Water,* 16(13), 1811.

National Academies of Sciences. (1983). Engineering, and Medicine. Safety of Existing Dams: Evaluation and Improvement (*Chapter 7: Embankment Dams*).

Pilotti, M., Milanesi, L., Bacchi, V., Tomirotti, M., & Maranzoni, A. (2020). Dam-break wave propagation in alpine valley with HEC-RAS 2D: experimental cancano test case. *Journal of Hydraulic Engineering,* 146 (6).

Heitland, J. & Donaghy, H. (2021). Seepage and Slope Stability Modeling for Embankment Dams (Guidance Document). Association of State Dam Safety Officials.

Butt, M. J., Umar, M., & Qamar, R. (2013). Landslide dam and subsequent dam-break flood estimation using HEC-RAS model in Northern Pakistan. Natural Hazards, 65(1), 241-254.

Haltas, I., Tayfur, G., & Elci, S. (2016). Two-dimensional numerical modeling of flood wave propagation in an urban area due to Ürkmez dam-break, İzmir, Turkey. *Natural Hazards,* 81(3), 2103-2119.

Azeez, O., Elfeki, A., Kamis, A. S., & Chaabani, A. (2020). Dam break analysis and flood disaster simulation in arid urban environment: The Um Al-Khair dam case study, Jeddah, Saudi Arabia. *Natural Hazards,* 100(3), 995-1011.

Ozmen-Cagatay, H., & Kocaman, S. (2010). Dam-break flows during initial stage using SWE and RANS approaches. *Journal of Hydraulic Research,* 48(5), 603-611.

Ozmen-Cagatay, H., & Kocaman, S. (2011). Dam-break flow in the presence of obstacle: experiment and CFD simulation. *Engineering applications of computational fluid mechanics,* 5(4), 541-552.

Kocaman, S., & Ozmen-Cagatay, H. (2015). Investigation of dam-break induced shock waves impact on a vertical wall. *Journal of Hydrology,* 525, 1-12.

LaRocque, L. A., Imran, J., & Chaudhry, M. H. (2013) a. Experimental and numerical investigations of two-dimensional dam-break flows. *Journal of Hydraulic Engineering,* 139(6), 569-579.

Larocque, L.A., Imran, J., & Chaudhry, M.H. (2013) b. 3D numerical simulation of partial breach dam-break flow using the LES and k–ϵ turbulence models. *Journal of Hydraulic Research,* 51(2), 145-157.

Esmaeeli Mohsenabadi, S., Nistor, I., Mohammadian, A., & Kheirkhah Gildeh, H. (2023). CFD modelling of initial stages of dam-break flow. *Canadian Journal of Civil Engineering,* 50(10), 838-852.

Kumcu, Ş. Y., & Uçar, M. (2020). Dolusavak yapılarının fiziksel ve sayısal modelleme yöntemi ile analizi. *Niğde Ömer Halisdemir Üniversitesi Mühendislik Bilimleri Dergisi,* 9(1), 350–357.

Aydın, M. C., & Kaplan, C. (2019). Ilısu Barajı dolusavak havalandırıcısı performans analizi. *Niğde Ömer Halisdemir Üniversitesi Mühendislik Bilimleri Dergisi,* 8(2), 902–911.

El-Hazek, A. N., Abdel-Mageed, N. B., & Hadid, M. H. (2020). Numerical and experimental modelling of slope stability and seepage water of earthfill dam. *Journal of Water and Land Development,* 44(I–III), 55–64.

Efe, H., & Önen, F. (2022). Batman Barajı'nın Yıkılma Analizi ve Baraj Güvenliği Açısından Değerlendirilmesi. *Dicle Üniversitesi Mühendislik Fakültesi Dergisi,* 13(1), 78–92.

Nikrou, P., & Pirboudaghi, S. (2024). Numerical analysis of cavitation dynamics on free ogee spillways using the Volume of Fluid (VOF) method. doi.org/10.48550/arXiv.2412.00695

Kemaloğlu, N.P., Koçyiğit, M.B., & Akay, H._ (2019). Rahmanlar Barajı Taşkın Senaryosu ve HEC-RAS Modeli ile Analizi. *Gazi Üniversitesi Fen Bilimleri Dergisi*, 32(4), 1100–1115.

Demir, F., Sarayli, S., Sonmez, O., Ergun, M., Baycan, A., & Tuncer Evcil, G. (2025). Two-Dimensional flood modeling of a piping-induced dam failure triggered by seismic deformation: a case study of the Doğantepe Dam. *Water,* 17(15), 2207.

Yenigün, K. (2001). Barajlarda Güvenilirlik ve Dolusavak Boyutlarının Risk Düzeyine Etkisi. Doktora Tezi, İstanbul Teknik Üniversitesi, Fen Bilimleri Enstitüsü.

Kaplan, C. (2018). Ilısu Barajı Dolusavak Havalandırıcısının Performans Değerlendirmesi. Yüksek Lisans Tezi, Bitlis Eren Üniversitesi, Fen Bilimleri Enstitüsü.

Yalçın, E. E., İkincioğulları, E., & Kaya, N. (2024). Üçgen Basamaklı Dolusavakların Enerji Sönümleme Performansının İncelenmesi. *Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi,* 30(4), 522-529.

Dursun, Ö. F., & Öztürk, M. (2009). Basamaklı Dolusavakların Akımın Enerjisini Sönümleme Özelliğinin Sayısal Analizi. *Journal of New World Sciences Academy,* 4(2), 165-174.

Büyüktaş, K., Tezcan, A., & Sajid, İ. (2017). Enerji Kırıcı Yapıların Etkinliğinin HAD Yöntemi ile Belirlenmesi. *Derim Dergisi,* 34(2), 172-181.

Çalışkan, B., & Uğur, A. (2024). Seyhan Barajı Mansap Bölgesi Taşkın Analizi ve Taşkın Risk Alanlarının Belirlenmesi. *Çukurova Üniversitesi Mühendislik Fakültesi Dergisi,* 39(4), 988–1004.

Garsore, A., Bokil, S., Kumar, V., Pandey, A., & Topare, N. S. (2023). A review of artificial intelligence methods for predicting gravity dam seepage: Challenges and way-out. *Water Infrastructure, Ecosystems and Society,* 72(7), 1228–1245.

Ghaderi, A., Shahini, H., Mohammadnezhad, H., Hamidifar, H., & Pu, J. H. (2025). Hydraulic Response of Dam-Break Flood Waves to Converging Channel Geometries: A Numerical Investigation. *Water,* 17(17), 2593.

## CHAPTER 3

# STONE FACADE CLADDING APPLICATIONS: MATERIAL SELECTION AND ON SITE INSTALLATION PRINCIPLES CONFORMITY ASSESSMENT, RISKS, AND PREVENTIVE APPROACH

Dr. Özlem ÖZKAN ÖNÜR

## INTRODUCTION

Therefore, a natural stone façade cladding system should be considered an integrated engineering solution its components are predefined, selected in line with performance criteria, and designed to work together as a coherent whole. In this context, the objective is to satisfy multi-dimensional design targets such as strength, service life, safety, and maintenance management alongside aesthetic requirements. System performance depends not only on material selection, but also on the simultaneous and coordinated functioning of the supporting substructure, bonding/anchoring chemical components, on site installation processes, and quality and safety control mechanisms.

Since deterioration mechanisms in stone materials can be accelerated by microclimatic effects, environmental conditions must be taken into account in façade design (Viles, 2013). For this reason, the types of decay observed in façade stones should be evaluated together with the stone's lithology and its exposure environment (Grossi et al., 2003). In two urban settings with different climatic conditions, the rates of black soiling on granite, marble, and limestone were investigated by positioning samples in sheltered and unsheltered locations, it was shown that overall darkening and soiling rates could be monitored through color-change measurements (Grossi et al., 2003). Deterioration processes may be triggered not only by atmospheric effects, but also by the stone's interaction with its immediate surroundings within the building system. In particular, corrosion of metal components used for supporting and anchoring stone elements can create harmful stresses in the stone and accelerate damage. In the Royal Palace of Madrid (Palacio Real), the production process and composition of iron ties and reinforcement used in the support and anchorage of stone elements were examined; it was reported that slag bands within the iron accelerate corrosion, leading to the formation of iron hydroxides such as lepidocrocite and subsequently goethite, and that the associated volume increase generates pressure within the stone, ultimately causing cracking and disintegration (Fort, Alvarez de Buergo, Mingarro, & López de Azcona, 2004).

Chemical incompatibility and salt crystallization are also among the principal deterioration mechanisms that limit stone durability. In the case of the Monastery of Santa Maria de Bonaval, it is emphasized that sulfate-containing mortars combined with magnesium-rich dolomitic stone/mortar systems can create chemical incompatibility, accelerating salt weathering due to the crystallization of $MgSO_4$ salts especially epsomite pore structure and capillary transport sustain this process, and such material combinations should therefore be avoided in restoration practice (López-Arce, Garcia-Guinea, Benavente, Tormo, & Doehne, 2009). Similarly, it is stated that salt crystallization generates stresses on pore surfaces and constrains the durability of porous building stones accordingly, stone durability should be assessed considering both pore-structure parameters and mechanical strength as an indicator of resistance to crystallization pressure (Benavente et al., 2004). Internal structural defects in stone such as cracks may facilitate the accumulation of environmental effects within the material and lead to strength losses. In ornamental granites, microcracks and porosity were reported to be decisive for physical-mechanical properties and durability the void system was found to consist mainly of microcracks and to be related to open porosity, and increasing linear crack density (LCD) generally corresponded to decreasing uniaxial compressive strength and P-wave velocity (Sousa et al., 2005). Another study showed that stone texture and anisotropy may also affect performance. In traditional dry-stone masonry structures in northwestern Portugal, the behavior of schist and granite was examined for schist, pronounced anisotropy influenced properties, whereas for granite, a more isotropic and compact texture was associated with higher strength and lower water absorption additionally, water was reported to adversely affect strength and elastic parameters of the stones (Barroso, Oliveira, & Ramos, 2020). In this respect, direct measurement of microclimate conditions strengthens the assessment of deterioration risk. Along the central Namib Desert in Namibia, rock-surface microclimate (surface temperature, air temperature, wind, relative humidity, and surface wetness) was monitored over the long term it was found that relative humidity and surface wetness differed substantially among sites due to fog frequency, and while granite blocks exhibited no visually apparent changes in the short term, marble blocks showed microstructural weakening within a shorter period (Viles, 2005). However, a single measurement approach is not sufficient to establish durability reliably. For evaluating durability in masonry structures, there is a need for both accelerated laboratory tests and non-destructive methods applicable in situ (RILEM TC 177-MDT, 2004). In this framework, the RILEM MDT.D.1 recommendation defines an indirect in-situ method for assessing mortar performance based on drilling energy (RILEM TC 177-MDT, 2004). Overall, the literature emphasizes that the deterioration of natural stone has increased markedly over the last century, and that the interaction of stone with both its immediate environment (building components and connection elements) and its macro-environment (climate and atmospheric conditions) should be addressed through a multidisciplinary approach (Siegesmund & Snethlage, 2011). Therefore, in mechanically anchored stone façades, the design approach should jointly consider environmental risks and the material compatibility of the stone-connection detail.

Within this framework, anchorage design in natural stone façade cladding is a key component that directly governs system performance, as it ensures that loads acting on stone panels such as self-weight and lateral actions are safely transferred to the structural system through connection points and that the forces at these points can be determined (European Organisation for Technical Assessment, 2018). The suitability assessment of slabs to be used in cladding applications has been addressed within the scope of EN 1469:2015, which defines requirements for geometric, physical, and mechanical properties as well as sampling, testing, and factory production control principles for stone cladding slabs (CEN, 2015). To characterize mechanical performance, uniaxial compressive strength was evaluated in accordance with EN 1926:2006 to determine behavior against water, the immersion at atmospheric-pressure water absorption test was evaluated in accordance with EN 13755:2008 (CEN, 2006; CEN, 2008). Finally, when discussing material choices that may influence the metal-stone interface behavior in anchorage details, findings from composite materials research provide a supportive framework showing that composition microstructure performance relationships can be decisive. In this context, it is noted that the material of the connector and the potential use of polymer-based interlayers-coatings (e.g., epoxy-based components) may affect service performance; therefore, material selection should be considered not only in terms of strength, but also with respect to interface behavior and durability (Şahin, 2023). Likewise, it has been shown that the type and amount of filler in composite design can be decisive for microstructure and performance, and that targeted functional performance can be improved through composite design (Emek et al., 2025).

The aim of this study is to present material conformity and on site installation principles from the perspective of performance, safety, and quality assurance by addressing the natural stone façade cladding system as an integrated engineering system whose components work in a compatible manner. Within the scope of the study, four main themes are examined the components of the mechanical supporting system and load-transfer principles, selection of chemical fixing and bonding solutions and compatibility conditions, on site installation methodology and critical application details, and control steps and acceptance criteria required for quality and safety assurance.

In the methodology, the technical documentation of project-approved system components is taken as the basis the tested performance data and conformity conditions of the selected materials are evaluated, and the on site installation workflow is analyzed through critical control points. The findings are classified in a way that makes compatibility among system components and application related risks explicit, and preventive approaches to risk reduction are defined together with quality assurance steps and site control criteria. Figure 1 presents the natural white cladding Syrian stone, and Figure 2 illustrates the schematic representation of a mechanically anchored natural stone façade cladding system, including the load-bearing wall, the natural stone panel fixed by a mechanical anchor and L-bracket, and the placement of the chemical adhesive (SHELBER) behind the panel.

**Figure 1**. Natural White Syrian Stone

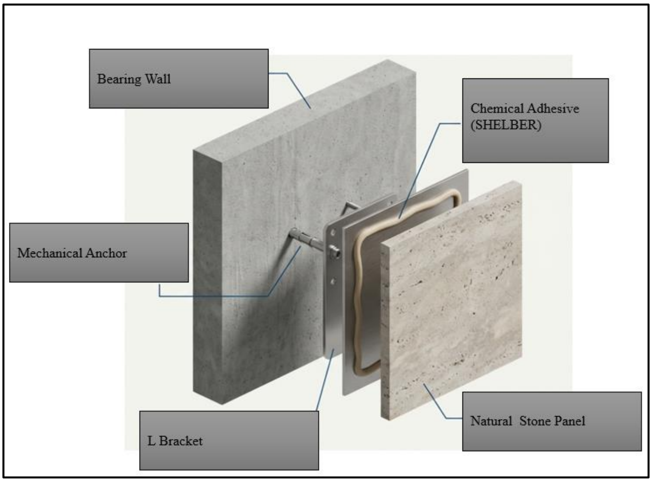



**Figure 2**. Schematic Representation of the Mechanically Anchored Natural Stone Façade Cladding System

**MECHANICAL SUPPORTING SYSTEM**

The mechanical supporting system is used in the form of stainless-steel L-bracket elements designed to safely transfer the vertical and horizontal loads from the façade cladding components to the main structural system. These L-brackets, which exhibit high corrosion resistance and whose mechanical strength has been verified through testing, are selected and validated in terms of material strength and corrosion behavior to ensure continuous performance under moisture and temperature variations caused by outdoor environmental conditions. In this respect, they constitute one of the key components that supports the sustainability of both structural safety and installation quality in natural stone façade cladding applications, in terms of load-bearing capacity, connection reliability, and long-term service life. As presented in Table 1, the technical specifications of the mechanical supporting system, Figure 3.a KBS MAX316, Figure 3.b Rockany L-bracket.

**Table 1.** Technical Specifications of the Mechanical Supporting System (L-Bracket)

| Property | Value | Source |
|---|---|---|
| Material Grade | Stainless Steel (SS 304 / SS 316) | Rockany Datasheet (A2/A4) KBS (MAX316) |
| Tensile Strength | 750 MPa | KBS MA 316 Datasheet |
| Surface Finish | Bright | KBS MA 316 Datasheet |
| Projection Range (Cavity) | 20 mm-90 mm | Rockany L-Bracket Datasheet |
| Stone Used | White Syrian | Method of Statement |
| Dimensions | 90×60×3 cm ve 90×6×3 cm | Method of Statement |

a) b)

**Figure 3.** a) KBS MAX316, b) Rockany L-Bracket

In the design of the mechanical supporting system, a wide product range of L-bracket and anchorage solutions with variable sizes and capacities is adopted, depending on cavity requirements and load levels, in order to safely carry the loads generated by the façade cladding and to accommodate different façade geometries. This approach enables the optimization of both the load-bearing capacity and installation tolerances of the substructure according to project-specific conditions, thereby improving the predictability of the stone cladding system in terms of structural behavior, connection safety, and long-term performance. Table 2 presents the L-bracket dimensions and anchor selection, and Figure 4 provides a schematic representation of the geometric parameters of the L-bracket.

**Table 2.** L-Bracket Dimensions and Anchor Selection

| Product Code | Cavity (mm) | Bracket Length (L-mm) | Bracket Thickness (T-mm) | Anchor |
|---|---|---|---|---|
| RKY-L-30/3 | 15 | 30 | 3 | M6 |
| RKY-L-50/4 | 35 | 50 | 4 | M8 |
| RKY-L-70/5 | 55 | 70 | 5 | M10 |
| RKY-L-90/6 | 75 | 90 | 6 | M10 |

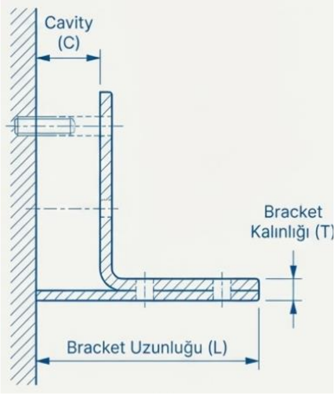



**Figure 4.** Schematic Representation of the Geometric Parameters of the L-Bracket

## CHEMICAL FIXING AND BONDING

Within the scope of chemical fixing and bonding, an unsaturated polyester resin-based SHELBER adhesive, featuring fast-curing properties and a suitable operating temperature range, is used to increase the safety of the stone panels. As shown in Figure 5, the unsaturated polyester resin-based SHELBER used for the chemical fixing and bonding of the stone panels is presented.


**Figure 5**. Polyester Resin-Based SHELBER (Marble Adhesive)

The mechanical performance of the SHELBER adhesive has been verified through independent laboratory testing, based on experiments conducted by the Geoscience Testing Laboratory (GTL) operating in Dubai. This verification supports traceable documentation of the performance of the chemical fixing and bonding component, providing a technical basis for material selection and quality assurance. As shown in Figure 6, tensile strength and flexural strength were adopted as the primary parameters for evaluating the mechanical performance of the adhesive.

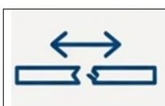
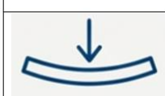
| | |
|---|---|
|  | Tensile Strenght |
|  | Flexural Strength |

**Figure 6**. Mechanical Performance of the Polyester Resin-Based SHELBER

## ON SITE WORK AND INSTALLATION PROCESS

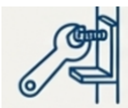
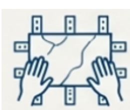
The on site installation process of stone cladding panels using the mechanical supporting L-bracket anchorage system is addressed together with the installation sequence and quality control stages. The field application starts with marking the anchor locations on the wall and verifying the measurements in accordance with the approved project drawings holes with the specified diameter and depth are then drilled to provide the base for the supporting system. As shown in Figure 7, the installation is carried out by a coordinated team working on scaffolding and a work platform. Occupational health and safety conditions are ensured through the use of personal protective equipment (PPE) such as hard hats and reflective vests. Following the placement of anchors and the fixation of L-brackets at the specified tightening values using a torque wrench, the stone panels are prepared for pin-dowel connections. The panels are then transported on site and seated onto the bracket system.

## ON SITE INSTALLATION STAGES

Preparation and measurement identifying and marking the anchor points on the wall in accordance with the approved drawings and verifying the axis lines, level (elevation), and alignment for drilling operations, drilling the anchor holes to the specified depth and diameter and ensuring the use of appropriate PPE and safe working conditions, in anchor and bracket installation, placing the anchors and fixing the L-brackets at the specified tightening values using a torque wrench, and checking connection rigidity and continuity in the preparation of stone panels, drilling the pin-dowel holes in the cutting area and making the panels suitable for installation, and checking the dimensions and hole locations in stone installation and alignment checks, transporting the panels on site through team coordination and placing them on the bracket system, and during installation checking the surface line, verticality, level (elevation), and depth alignment and making adjustments if necessary; and in jointing and cleaning, applying joint filler in the required areas. At the end of the installation, the surfaces are cleaned with clean water to ensure visual integrity and completion conditions. As shown in Figure 7, the on site installation of the stone panels using the mechanical supporting system (anchors and L-brackets) and the alignment checks are presented, while Table 3 provides the on site work and installation method.

**Figure 7.** On Site Installation of Stone Panels Using the Mechanical Supporting System (Anchors and L-Brackets) and Alignment Checks

**Table 3.** On Site Work and Installation Method

| Stage | Activity | Control Points |
| --- | --- | --- |
|  | Preparation and Measurement | Identifying and marking the anchor locations on the wall in accordance with the approved drawings, and verifying the gridlines (axes), levels (elevations), and alignment. |
|  | Drilling Operations | Drilling the anchor holes to the specified diameter and depth, while ensuring the use of appropriate PPE and maintaining safe working conditions. |
|  | Anchor and Bracket Installation | Installing the anchors and fixing the L-brackets to the specified tightening torque using a torque wrench, followed by checks for connection rigidity and continuity. |
|  | Stone Preparation | Drilling the pin–dowel holes in the cutting/preparation area and making the stone panels ready for installation; verifying panel dimensions and hole locations. |
|  | Stone Installation | Drilling the pin-dowel holes in the cutting preparation area and making the stone panels ready for installation; verifying panel dimensions and hole locations. |
|  | Jointing and Cleaning | If required, applying joint filler; after installation, cleaning all surfaces with clean water and ensuring overall visual integrity. |

## OCCUPATIONAL HEALTH AND SAFETY (OHS) KEY HAZARDS AND PREVENTIVE MEASURES

As shown in Table 4, the occupational health and safety (OHS) findings indicate that stone cladding works on site involve multiple hazard classes simultaneously. During the application process, activities carried out on scaffolding are considered work at height therefore, protective measures such as guardrails must be provided to reduce the risk of falls. In addition, the areas below must be controlled with safety barriers tape, and the work should be carried out only by qualified personnel. Exposure to respirable dust generated during cutting and drilling operations should be limited through the use of appropriate respiratory protective equipment and engineering controls such as local exhaust ventilation (LEV). Cleaning should be performed using vacuum systems to prevent secondary dust generation. To reduce musculoskeletal strain resulting from the manual handling of panels and equipment, individual lifting limits should be set, training on safe lifting techniques should be provided, and two person handling should be adopted when necessary. The use of power tools is also critical in terms of electrical hazards and trip risks caused by cables it must be verified that equipment operates at the appropriate 220 V voltage periodic inspections must be conducted, and cable management should be maintained in an orderly manner.

**Table 4.** Potential hazards during natural stone façade installation on site, associated risk definitions, and recommended preventive measures.

| Hazard | Risk | Preventive measures |
|---|---|---|
|  | Hazard risk preventive measures | Providing guardrails and toe boards on scaffolds and platforms cordoning off elevated areas with safety tape barriers ensuring that only qualified competent personnel carry out the work. |

| | | |
|---|---|---|
|  | Respirable dust during cutting, drilling, etc. | Using FFP2 masks carrying out dusty works with local exhaust ventilation (LEV) cleaning with appropriate vacuum systems health surveillance. |
|  | Musculoskeletal strain due to handling heavy elements | Limiting the maximum lifting weight per person to 20 kg providing training on safe lifting techniques; using two-person handling when necessary. |
|  | Electric shock, cable-related tripping, and equipment failure | Ensuring all equipment is suitable for 220 V performing weekly tool inspections; keeping cables organized and ensuring they do not create trip hazards. |

## CONCLUSION

In this study, the natural stone façade cladding application was evaluated as an integrated engineering system in which the project-specific mechanical supporting substructure anchor, L-bracket, chemical fixing/adhesive components, on site application methodology, and quality and occupational health and safety (OHS) assurance are addressed together. The assessment based on project-approved technical documentation and verified performance data shows that system performance depends not only on the properties of individual materials, but primarily on the continuity of compatibility between components and the disciplined implementation of the defined on-site workflow. Within the mechanical support system, the fact that key mechanical parameters of the stainless-steel L-bracket elements SS 304 and SS 316 uch as corrosion behavior and tensile strength are supported by technical data and tests constitutes the main basis of structural safety for the secure transfer of façade loads to the primary structure. According to project requirements, the selection of bracket–anchor combinations with different cavity sizes and dimensions should be ensured in order to achieve conformity to the façade geometry, manage installation stages effectively, and improve repeatability of the application. For the chemical fixing and bonding stage, choosing a fast-curing product with a wide operating temperature range and performance verified by tests is important for quality assurance. For on site execution, after setting-out and measurement checks are carried out in accordance with the approved drawings, the anchor holes should be drilled to the specified diameter and depth, the brackets should be installed with torque control, and the stone panels should be prepared for pin-dowel connections. Completing the work with jointing and cleaning is an important step for maintaining continuity of workmanship quality and ensuring the sustainability of the installation.

In this study, the on-site inspection and control stages for the approved components should be conducted in integration with Occupational Health and Safety (OHS) practices. This provides an applicable method to support the safe and long-lasting performance of natural stone façade cladding systems and to achieve structural safety and maintenance management objectives throughout the service life.

## REFERENCES


Barroso, C. E., Oliveira, D. V., & Ramos, L. F. (2020). Physical and mechanical characterization of vernacular dry stone heritage materials: Schist and granite from Northwest Portugal. Construction and Building Materials, 259, 119705.

Benavente, D., García del Cura, M. A., Fort, R., & Ordóñez, S. (2004). Durability estimation of porous building stones from pore structure and strength. Engineering Geology, 74(1-2), 113-127.

Emek, M., Şahin, E. İ., Ibrahim, J.-E. F. M., & Kartal, M. (2025). Electromagnetic shielding performance of Ta-doped $NiFe_2O_4$ composites reinforced with chopped strands for 7-18 GHz applications. Nanomaterials, 15(20), 1580. https://www.mdpi.com/2079-4991/15/20/1580.

European Committee for Standardization. (2015). EN 1469:2015: Natural stone products-Slabs for cladding-Requirements. CEN.

European Committee for Standardization. (2016). EN 13755:2008: Natural stone test methods-Determination of water absorption at atmospheric pressure. CEN.

European Committee for Standardization. (2016). EN 1926:2006: Natural stone test methods-Determination of compressive strength. CEN.

European Organisation for Technical Assessment. (2018). EOTA Technical Report TR 062: Design of fasteners for façade panels made of natural stone (except slate) and ceramic tiles (stoneware). EOTA.

Fort, R., Alvarez de Buergo, M., Mingarro, F., & López de Azcona, M. C. (2004). Stone decay in 18th century monuments due to iron corrosion: The Royal Palace, Madrid (Spain). Building and Environment, 39(3), 357-364. https://doi.org/10.1016/j.buildenv.2003.09.012.

Grossi, C. M., Esbert, R. M., Díaz-Pache, F., & Alonso, F. J. (2003). Soiling of building stones in urban environments. Building and Environment, 38, 147-159. https://doi.org/10.1016/S0360-1323(02)00017-3.

Ibrahim, J. E. F. M., Tihtih, M., Şahin, E. İ., Basyooni, M. A., & Kocserha, I. (2023). Sustainable zeolitic tuff incorporating tea waste fired ceramic bricks: Development and investigation. Case Studies in Construction Materials, 19, e02238. https://doi.org/10.1016/j.cscm.2023.e02238.

López-Arce, P., Garcia-Guinea, J., Benavente, D., Tormo, L., & Doehne, E. (2009). Deterioration of dolostone by magnesium sulphate salt: An example of incompatible building materials at Bonaval Monastery, Spain. Construction and Building Materials, 23(2), 846-855. https://doi.org/10.1016/j.conbuildmat.2008.04.001.

RILEM TC 177-MDT. (2004). Test method recommendations of RILEM TC 177-MDT, Masonry durability and on-site testing. Indirect determination of the surface strength of unweathered hydraulic cement mortar by the drill energy method. Materials and Structures, 37, 485-487. https://doi.org/10.1007/BF02481586.

Siegesmund, S., & Snethlage, R. (2011). Stone in architecture: Properties, durability, Springer.

Sousa, L., Suárez del Río, L. M., Calleja, L., Rodríguez-Rey, A., & Ruiz de Argandoña, V. G. (2005). Influence of microfractures and porosity on the physico-mechanical properties and weathering of ornamental granites. Engineering Geology, 77(1-2), 153-168.

Şahin, E.İ. (2023). Electromagnetic shielding effectiveness of $Ba(Zn_{1/3}Nb_{2/3})O_3$:Chopped strands composites for wide frequency applications. Journal of Ceramic Processing Research, 24(1), 190-196.

Viles, H. A. (2005). Microclimate and weathering in the central Namib Desert, Namibia. Geomorphology, 67(1-2), 189-209. https://doi.org/10.1016/j.geomorph.2004.04.006.

ENGINEERING DESIGN AND SAFETY ANALYSIS: SUSTAINABILITY, RISK, AND CONSTRUCTION PRACTICES

ISBN: 978-6-25575-375-5

9 786255 753755