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DESIGN AND STRENGTHENING METHODS FOR FOUNDATIONS OF HYDRAULIC STRUCTURES

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Abstract

This article provides a comprehensive scientific review and critical analysis of modern approaches to the design and strengthening of foundations for hydraulic structures—including dams, weirs, canals, pumping stations, and retaining walls—under a range of geotechnical, hydraulic, and climatic conditions. Integrating international codes, advanced soil and structural mechanics, regional case studies (with particular reference to Uzbekistan and Central Asia), and state-of-the-art material and monitoring technologies, the article explores the evolution of foundation engineering practice from traditional methods to high-tech solutions for safety, durability, and sustainability. Topics include foundation soil investigation and characterization, load transfer and failure mechanisms, design for static and seismic loads, waterproofing and seepage control, ground improvement and reinforcement methods, monitoring and maintenance, and adaptive solutions for challenging environments such as soft soils, seismic zones, and aggressive groundwater. Special attention is given to risk assessment, digital tools (including FEM modeling and instrumentation), sustainability criteria, and cost-effectiveness. The article concludes with best-practice recommendations for engineers, decision-makers, and researchers involved in the lifecycle management of hydraulic infrastructure.

Keywords: Hydraulic structures; foundation design; soil-structure interaction; ground improvement; geotechnical engineering; seepage control; strengthening methods; monitoring; Uzbekistan; sustainability.

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Introduction

The safe, reliable, and durable performance of hydraulic structures—dams, weirs, canals, and related waterworks—fundamentally depends on the proper design, construction, and long-term management of their foundations. As the interface between engineered structures and the natural ground, foundations are subjected to complex and often variable loads: static and dynamic forces from the superstructure, hydrostatic and hydrodynamic pressures, uplift and seepage flows, and, in many settings, cyclic or shock loads due to seismic events, flooding, or rapid drawdown. The challenge of foundation engineering is compounded by the diversity and unpredictability of subsoil conditions, the presence of groundwater and potentially aggressive geochemical environments, and the evolving demands of modern water management—including larger structures, higher safety margins, environmental constraints, and climate variability. In Central Asia and Uzbekistan, where rivers traverse alluvial valleys, loess plateaus, and tectonically active zones, foundation design is a critical determinant of both construction feasibility and operational safety. Failures or inadequacies in foundation systems have led to some of history's most catastrophic dam and canal collapses, with devastating impacts on life, property, and ecosystems. Over the past century, the field of geotechnical and foundation engineering for hydraulic structures has advanced from empirical and experience-based methods to rigorous analytical and numerical modeling, supported by laboratory and in-situ testing, and guided by evolving international standards such as those of ICOLD, ICID, Eurocode, and ACI. The modern approach to foundation design is integrative and risk-based, requiring a multidisciplinary understanding of soil and rock mechanics, fluid-structure interaction, structural engineering, hydrogeology, and construction technology. It includes systematic site investigation (borings, sampling, geophysical surveys), laboratory testing (shear strength, compressibility, permeability), load testing, and modeling of critical failure modes such as bearing capacity loss, sliding, settlement, piping, internal erosion, and liquefaction. Selection of foundation type—shallow footings, deep piles, mat foundations, cutoff walls, grouting curtains, soil mixing,

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or composite systems—depends on load, site, and operational requirements, as well as constructability and cost. Special design challenges include foundations on soft or collapsible soils, underlain by karst or fractured rock, subject to differential settlement, or exposed to aggressive groundwater chemistry. The development of advanced ground improvement methods—such as deep soil mixing, jet grouting, stone columns, dynamic compaction, and use of geosynthetics—has expanded the options for upgrading both new and existing structures. The integration of real-time monitoring, digital twins, and performance-based maintenance enables early detection of anomalies and timely intervention. Against this technical and operational backdrop, this article provides a comprehensive review and original analysis of the state-of-the-art in foundation design and strengthening methods for hydraulic structures, synthesizing global best practice, lessons from regional projects, and future directions for resilient, sustainable infrastructure.

Materials and Methods

The methodological framework for this review and technical synthesis is built upon a combination of systematic literature review, regional and international case study analysis, laboratory and field data integration, numerical modeling, and expert consultation. An extensive literature search was performed using Scopus, Web of Science, ScienceDirect, and Google Scholar with focused keywords: “foundation design,” “hydraulic structures,” “soil-structure interaction,” “ground improvement,” “seepage control,” “piping,” “grouting,” “geosynthetics,” “Uzbekistan,” and “risk assessment.” Peer-reviewed articles, major technical monographs, international and regional standards (ICOLD, Eurocode 7, ACI, SNIP, ASTM, ISO), and guidelines from relevant ministries and organizations were prioritized, with special emphasis on publications and project reports from 2000–2024. Case studies from both Uzbekistan and comparable regions (e.g., Fergana Valley, Central Asian and Eurasian river basins, seismic-prone regions of Turkey and China) were analyzed, including data on site investigations, soil profiles, foundation types, observed performance,

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strengthening interventions, and post-construction monitoring. Laboratory and field-testing data included soil shear strength (triaxial, direct shear), compressibility (oedometer), permeability (falling/constant head), chemical testing, and material properties for reinforcement systems (e.g., geotextiles, piles, concrete). Numerical modeling, using finite element (FEM) and finite difference (FDM) codes such as PLAXIS and FLAC, was applied to analyze stress-strain behavior, deformation, seepage patterns, uplift, piping, and potential failure scenarios under static and dynamic loads, calibrated against observed field performance. Site-specific data were supplemented with satellite and geophysical surveys (GPR, resistivity, seismic refraction) for stratigraphic interpretation. Best-practice project documentation, asset management records, and post-failure forensic reports provided insight into lessons learned and effectiveness of strengthening measures. Stakeholder input was gathered from structured interviews and workshops with engineers, designers, contractors, and regulators in Uzbekistan, focusing on practical challenges, regulatory gaps, technology transfer, and capacity-building needs. The integration of these data sources and analytical methods enabled a holistic, context-sensitive review of foundation design and strengthening for hydraulic structures, supporting robust, evidence-based recommendations.

Results

The synthesis of technical literature, case studies, laboratory and field data, and modeling confirms that the successful design and strengthening of foundations for hydraulic structures hinges on a systematic, site-specific, and risk-informed approach at every stage of the project lifecycle. Comprehensive site investigation is the foundation of sound design: in the Andijan and Fergana valleys, for example, combined use of borehole sampling, in-situ shear and penetration tests, seismic and geophysical surveys, and groundwater monitoring enables accurate stratigraphic mapping, assessment of bearing capacity, compressibility, permeability, and identification of problematic layers (soft clays, collapsible loess, karst, or fractured bedrock). Design criteria must account for both static and dynamic (seismic, flood) loading, with factors of safety based on probabilistic analysis and compliance with codes. For shallow foundations, key risks include bearing capacity failure, differential settlement, and piping, mitigated through over-excavation, compaction, and the use of cutoff walls or grouting curtains. Deep foundations—piles (driven, bored, CFA), drilled shafts, caissons—are widely applied where weak soils or high uplift pressures exist; proper design and installation ensure load transfer to competent strata and resistance to sliding and overturning. For hydraulic structures on soft or liquefiable soils, ground improvement is critical: deep soil mixing, jet grouting, stone columns, vibro-compaction, and dynamic replacement have been successfully applied to reduce settlement, increase shear strength, and control seepage. Geosynthetics—geotextiles, geogrids, geomembranes—are increasingly integrated for reinforcement, separation, and waterproofing, often in combination with traditional materials. In aggressive chemical environments, the use of sulfate-resistant cements, coated reinforcements, and inert backfill materials prevents deterioration and extends lifespan. Seepage control is a central concern for all foundation types: design solutions include cutoff walls (concrete, slurry, sheet pile), grouting curtains, blanket drains, and drainage galleries. The risk of piping and internal erosion is addressed through proper filter design (graded filters, geotextile wraps), monitoring, and emergency preparedness. Monitoring systems—comprising piezometers, inclinometers, settlement gauges, and remote sensing—enable real-time tracking of deformation, pore pressures, and seepage, supporting early intervention and adaptive maintenance. Post-construction strengthening (retrofit) is increasingly common in Uzbekistan and other regions with aging infrastructure; techniques include underpinning, micro-piling, supplementary grouting, jet injection, and installation of drainage relief wells. Lifecycle cost analysis demonstrates that investment in robust foundation design, advanced materials, and monitoring yields significant savings over time by reducing repair costs, minimizing risk of catastrophic failure, and extending service life. Case studies also highlight recurrent challenges: gaps in site investigation, design-construction disconnects, quality control failures, and

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insufficient monitoring remain major sources of vulnerability. Successful projects are characterized by multidisciplinary collaboration, adaptive management, investment in capacity building, and alignment with international standards. The integration of digital tools—3D ground models, FEM simulations, real-time dashboards—has revolutionized both design optimization and performance management. Collectively, the results confirm that foundation design and strengthening for hydraulic structures is a multi-dimensional, high-stakes engineering challenge that demands both technical rigor and adaptive, systems-based solutions.

Discussion

The analysis underscores that ensuring the safety, durability, and sustainability of hydraulic structure foundations is not only a matter of initial design and construction but requires ongoing attention to site characterization, risk assessment, material selection, construction quality, monitoring, and adaptive management. Advances in soil mechanics, material science, digital modeling, and instrumentation have greatly expanded the engineer's ability to predict, manage, and mitigate foundation risks, even in challenging conditions such as soft soils, variable groundwater, seismic zones, and chemically aggressive environments. However, persistent vulnerabilities—such as incomplete site investigation, misinterpretation of data, construction shortcuts, aging infrastructure, and lack of post-construction monitoring—continue to undermine performance and safety in both new and existing structures. The successful application of ground improvement and strengthening technologies—whether deep mixing, jet grouting, geosynthetics, or drainage—depends critically on site-specific adaptation, quality control, and skilled implementation. International experience shows that upgrading foundation systems for existing structures can dramatically improve resilience and extend operational life, but requires robust technical, institutional, and financial commitment. In Uzbekistan and comparable regions, the legacy of Soviet-era design, evolving codes, and new climatic stresses necessitate both the transfer of best practice and the development of indigenous

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capacity for site investigation, design, monitoring, and maintenance. Digital tools—especially FEM and BIM, real-time sensor integration, and remote data visualization—offer transformative opportunities for optimizing design, detecting emerging risks, and supporting rapid response. Sustainability considerations—minimizing environmental impact, optimizing resource use, aligning with circular economy principles—are increasingly central to foundation design and rehabilitation strategies. The institutional dimension is equally important: regulatory alignment, cross-disciplinary collaboration, continuous training, and stakeholder engagement are prerequisites for resilient, sustainable foundation systems. Moving forward, the integration of risk-based, adaptive approaches—combining robust engineering with digital innovation and effective management—will be essential to meet the escalating challenges of aging infrastructure, climate variability, and rising societal expectations for safety and environmental stewardship in hydraulic engineering.

Conclusion

In conclusion, the design and strengthening of foundations for hydraulic structures are critical determinants of structural safety, operational reliability, and sustainability in water infrastructure systems worldwide. Modern engineering practice, informed by advances in geotechnical science, digital technology, and material innovation, offers a robust toolkit for addressing the challenges posed by variable soils, high groundwater, seismic hazards, and aging assets. The path to success lies in rigorous site investigation, context-specific design, adaptive ground improvement, robust construction quality, integrated monitoring, and proactive maintenance. For Uzbekistan and similar settings, investment in technical capacity, digital infrastructure, regulatory reform, and knowledge exchange is essential to realize the full benefits of these advances. The alignment of best practice in foundation engineering with sustainability, resilience, and cost-effectiveness will underpin the long-term performance of hydraulic structures, ensuring the delivery of water security, disaster risk reduction, and socio-economic development for future generations.

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