ADVANCING ENGINEERING FOR A SUSTAINABLE FUTURE (AE4SF)

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PROCEEDINGS

Dhrupodi 94's 1st International Symposium

1st International Symposium

Harrison Hot Springs, British Columbia, Canada

July 4, 2026

Hosted by the Dhrupodi Foundation, Canada

Organized by the BUET '94 Alumni Community

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About the Symposium

Dhrupodi 94's 1st International Symposium

Advancing Engineering for a Sustainable Future

The 1st International Symposium is a multidisciplinary forum that fosters collaboration among researchers, educators, industry leaders, entrepreneurs, policymakers, and students committed to advancing engineering solutions for a sustainable future. Organized by the BUET '94 alumni community and the **Dhrupodi Foundation**, this symposium serves as a platform for knowledge exchange, innovation sharing, and partnership strengthening across academia, industry, government, and society.

A quarter of a century since graduating from the Bangladesh University of Engineering and Technology (BUET), the members of the 1994 class have established professional careers across universities, research institutions, government agencies, multinational corporations, consulting organizations, healthcare systems, and entrepreneurial ventures around the world. This symposium celebrates that shared legacy while creating opportunities for global engagement, lifelong learning, and future collaboration.

The theme, **"Advancing Engineering for a Sustainable Future,"** reflects the engineering profession's responsibility to address the increasingly complex challenges of the twenty-first century. Climate change, resilient infrastructure, sustainable energy, urbanization, healthcare innovation, digital transformation, artificial intelligence, advanced manufacturing, and environmental stewardship require integrated engineering solutions that transcend traditional disciplinary boundaries.

The symposium welcomes contributions from a broad spectrum of engineering disciplines, including:

- Civil and Environmental Engineering
- Mechanical Engineering
- Electrical and Electronic Engineering
- Computer Science and Engineering
- Architecture and the Built Environment
- Chemical Engineering
- Materials and Metallurgical Engineering
- Naval Architecture and Marine Engineering

Recognizing the rapid convergence of engineering with digital technologies, the symposium places particular emphasis on **artificial intelligence, machine learning, data science, computer vision, digital twins, intelligent infrastructure, automation, robotics, and smart engineering systems**. It also highlights sustainable materials, resilient infrastructure, healthcare engineering, renewable energy, climate adaptation, and engineering entrepreneurship as key drivers of future innovation.

The technical program consists of **extended abstracts, full papers, and industry case studies**, providing a balanced representation of emerging research, practical engineering solutions, and real-world implementation experiences. Complementing the technical submissions, a special panel discussion on **Artificial Intelligence and the Future of Education, Careers, and Entrepreneurship**, has been arranged, creating opportunities for interdisciplinary dialogue and collaboration.

Beyond its technical objectives, the symposium strengthens the global BUET alumni network, encourages mentorship of the next generation of engineers, promotes industry-academia partnerships, and inspires innovative solutions that contribute to sustainable economic and societal development.

As the inaugural edition of what is envisioned as a recurring international event, the Dhrupodi 94’s International Symposium aims to evolve into a globally recognized forum for engineering excellence, innovation, leadership, and collaboration, bringing together diverse perspectives to help shape a more sustainable, resilient, and technologically advanced future.

Preface

Advancing Engineering for a Sustainable Future

Dhrupodi 94's **1st International Symposium** marks a defining moment for the global engineering community, convening leaders from academia, industry, government, and enterprise to advance solutions for the most pressing challenges of the twenty-first century. Organized by the BUET '94 Alumni Community and hosted by the **Dhrupodi Foundation**, this inaugural symposium reflects a shared commitment to advancing engineering solutions that contribute to a more sustainable, resilient, and technologically advanced world.

Engineering today is undergoing an unprecedented transformation driven by rapid technological innovation, artificial intelligence, digitalization, climate change, and increasing societal expectations for sustainable development. The symposium was conceived to provide an interdisciplinary platform for experts from diverse engineering disciplines to share emerging research, practical experiences, and innovative ideas, while strengthening collaborations among academia, industry, government, and entrepreneurs.

The primary objectives of the symposium are to:

- Promote excellence in engineering research and professional practice.
- Foster interdisciplinary collaboration across engineering, architecture, and technology.
- Showcase emerging innovations in artificial intelligence, machine learning, digital engineering, sustainability, healthcare technologies, advanced manufacturing, and resilient infrastructure.
- Strengthen partnerships between academia, industry, and government.
- Inspire students and early-career professionals to become future engineering leaders and innovators.
- Bring together Dhrupodi members from around the world and enable collaboration.

These proceedings represent the collective contributions of researchers and practitioners from universities, government agencies, consulting organizations, healthcare institutions, and industry across several countries. The papers encompass **extended abstracts** presenting emerging research, full papers, and **case studies** highlighting practical engineering solutions.

The contributions span a broad spectrum of topics, including:

- Artificial Intelligence and Machine Learning in Engineering
- Structural Health Monitoring and Computer Vision
- Sustainable and Resilient Infrastructure
- Earthquake Engineering
- Smart Materials and Construction Technologies
- Healthcare Engineering and Digital Health
- Automation, Robotics, and Manufacturing
- Energy Systems and Climate Technologies

- Environmental and Geotechnical Engineering
- Aviation and Marine Engineering
- Engineering Education and Workforce Development

A notable theme emerging throughout these proceedings is the convergence of traditional engineering disciplines with artificial intelligence and data-driven technologies. Several papers explore AI-enabled structural health monitoring, computer vision for infrastructure inspection, intelligent healthcare systems, AI-assisted weather prediction, and the evolving role of AI in engineering education. Others present innovative engineering solutions addressing sustainability, infrastructure resilience, industrial automation, renewable energy, and integrated design practices.

The organizing committee extends its sincere appreciation to all authors, reviewers, panelists, sponsors, volunteers, and participants whose dedication and expertise have made this inaugural symposium possible. We are particularly grateful to the Dhrupodi Foundation for hosting this event and to our industry partners for supporting knowledge exchange between academia and professional practice.

It is our hope that these proceedings will serve not only as a record of the symposium but also as a valuable reference that stimulates future research, innovation, interdisciplinary collaboration, and engineering solutions that improve society.

We wish all readers an informative and inspiring experience.

Shahria Alam, PhD, PEng
Editor, Proceedings of the 1st International Symposium on
Advancing Engineering for a Sustainable Future 2026

Welcome Messages

Message from the Conference Chair

It is my distinct pleasure to welcome you to the **Dhrupodi 94's 1st International Symposium: *Advancing Engineering for a Sustainable Future*.**

This symposium represents the collective vision of the BUET 94 alumni community to establish a global platform where engineering professionals, researchers, educators, entrepreneurs, and students can come together to exchange ideas and explore innovative solutions to the challenges facing our world.

Engineering is evolving rapidly through the integration of artificial intelligence, machine learning, digital technologies, advanced materials, and sustainable design principles. At the same time, society faces increasingly complex challenges related to climate change, resilient infrastructure, energy transition, healthcare, and sustainable urban development. Addressing these challenges requires interdisciplinary collaboration that bridges traditional engineering disciplines with emerging technologies.

The technical program reflects this vision by bringing together contributions from Civil, Mechanical, Electrical and Electronic, Computer Science, Chemical, Materials and Metallurgical, Naval and Marine Engineering, Architecture, and related fields. The proceedings include both research-oriented extended abstracts and industry-driven case studies, demonstrating the strong connection between academic innovation and engineering practice.

I extend my sincere appreciation to all authors, reviewers, speakers, panelists, sponsors, volunteers, and members of the organizing committee whose dedication has made this inaugural symposium possible.

I hope this symposium inspires new collaborations, lifelong friendships, and innovative engineering solutions that contribute to a more sustainable and prosperous future.

Shahria Alam, PhD, P.Eng.
Conference Chair, 1st International Symposium on
Advancing Engineering for a Sustainable Future 2026

Message from the Organizing Committee

On behalf of the Organizing Committee, we are delighted to welcome all participants to the inaugural Dhrupodi 94’s International Symposium.

This symposium has been established to promote technical excellence, professional networking, and interdisciplinary collaboration among engineers and researchers worldwide. We are particularly pleased to present a program that combines emerging academic research with practical engineering case studies, providing a unique forum where innovative ideas can be translated into real-world impact.

The committee gratefully acknowledges the valuable contributions of our authors, reviewers, keynote speakers, sponsors, industry partners, and volunteers. Their dedication and enthusiasm have been instrumental in making this symposium a reality.

We hope the technical sessions, panel discussions, networking opportunities, and industry interactions will stimulate meaningful dialogue and foster long-lasting collaborations that extend well beyond this event.

We thank you for your participation and wish you a productive and enjoyable symposium.

Hamid Zaman, PhD, PEng
On behalf of the Organizing Committee
Dhrupodi 94's 1st International Symposium on
Advancing Engineering for a Sustainable Future 2026

Message from the Host Institution

Dhrupodi Foundation Canada

The Dhrupodi Foundation Canada is honored to host the inaugural Dhrupodi 94's International Symposium and to support this important initiative that brings together distinguished engineers, researchers, innovators, educators, and industry leaders from around the world.

Our Foundation believes that sustainable development depends upon the integration of knowledge, innovation, ethical leadership, and lifelong learning. Engineering has always played a central role in improving the quality of life, and today its impact is expanding through advances in artificial intelligence, digital technologies, sustainable infrastructure, healthcare innovation, clean energy, and intelligent manufacturing.

By supporting this symposium, we aim to encourage the exchange of ideas across disciplines, strengthen connections between academia and industry, promote entrepreneurship and innovation, and inspire future generations of engineers to address global challenges with creativity, integrity, and social responsibility.

We congratulate the BUET '94 alumni community for their vision and leadership in organizing this international event and extend our best wishes for a successful symposium. We look forward to supporting future events and to seeing this symposium grow into a globally recognized forum for engineering excellence and innovation in the years ahead.

Anjuman Shahriar, PhD, PEng
President
Dhrupodi Foundation Canada

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Panel Discussion

Artificial Intelligence and the Future of Education, Careers, and Entrepreneurship

PART I

Sustainability and Resilience

Papers 001–005

Integrated Geotechnical, Environmental, and Site Development Considerations for a Multi-Storey Residential Development in Hinton, Alberta

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ABSTRACT: Mountain View Hinton is a proposed four-storey residential apartment development in Hinton, Alberta, on a site constrained by ravine-adjacent topography, variable subsurface conditions, unknown fill, and cold-region climatic exposure. The project required integrated consideration of environmental due diligence, geotechnical investigation, grading, drainage control, excavation planning, foundation feasibility, and climate-responsive building-envelope design. Phase I and Phase II environmental investigations were undertaken to assess the significance of unknown fill and potential soil and groundwater impacts, while a geotechnical site investigation was completed to characterize subsurface conditions and support foundation and earthworks planning. Reported subsurface conditions generally comprised sand and gravel fill underlain by sandstone and/or silty sand to depths of approximately 9 m. The site also required evaluation of ravine-interface constraints, including drainage management and long-term slope-related performance. This paper presents the project as a technical case study in integrated residential site engineering and demonstrates how early coordination of environmental and geotechnical findings informed site layout, below-grade development, and durability-oriented design decisions. The case illustrates that, for constrained residential developments in western Canadian conditions, technical decisions related to subsurface risk, drainage, constructability, and envelope performance are most effective when addressed within a unified engineering framework.

Keywords: geotechnical investigation; environmental site assessment; residential development; slope stability; retaining wall; drainage

1. INTRODUCTION

Residential developments in foothill and mountain-interface regions commonly present a more complex engineering environment than comparable projects on level urban parcels. In such settings, design feasibility is influenced not only by architectural programming and municipal servicing, but also by topography, subsurface variability, drainage pathways, slope geometry, climatic exposure, and regulatory constraints. Consequently, these projects require integrated evaluation of site planning, geotechnical conditions, environmental due diligence, infrastructure servicing, and long-term constructability.

Mountain View Hinton is a representative example of this development condition. The project is located near the intersection of Yellowhead Highway (HWY-16) and McArdell Drive in Hinton, Alberta, on a site influenced by irregular topography, ravine adjacency, and winter-weather exposure. The proposed development consists of a four-storey residential apartment building containing 43 dwelling units, together with underground parking, surface parking, bicycle storage, and landscaped amenity space. The site also benefits from access to existing municipal infrastructure and regional transportation connectivity.

The technical significance of the project arises from the need to address environmental due diligence, subsurface characterization, slope-related constraints, drainage control, and climate-responsive durability within a single development framework. Environmental investigations identified unknown fill requiring further assessment, while geotechnical investigation identified fill, sandstone, and silty sand strata through borehole drilling and field testing. These conditions directly influence excavation planning, foundation selection, retaining requirements, groundwater management, and long-term serviceability [2]. Alberta's tiered remediation framework recognizes that site-specific conditions may require assessment beyond generic assumptions [1], while the Canadian Foundation Engineering Manual emphasizes the importance of investigation quality and groundwater characterization in reducing foundation and construction risk [2].

This paper presents Mountain View Hinton as a case study in integrated residential site engineering under Western Canadian conditions. The objective is to examine how environmental review, geotechnical investigation, ravine-edge considerations, drainage measures, and cold-climate and resilience-driven design responses can be synthesized into a practical engineering solution for a multi-storey residential development (Fig. 2).

2. PROJECT SETTING AND DEVELOPMENT PROGRAM

A. Site Location And Layout

The Mountain View Hinton development is located near the intersection of Yellowhead Highway (HWY-16) and McArdell Drive in Hinton, Alberta, on Lot 1, Block 14, Plan 8321567 (Fig. 1).

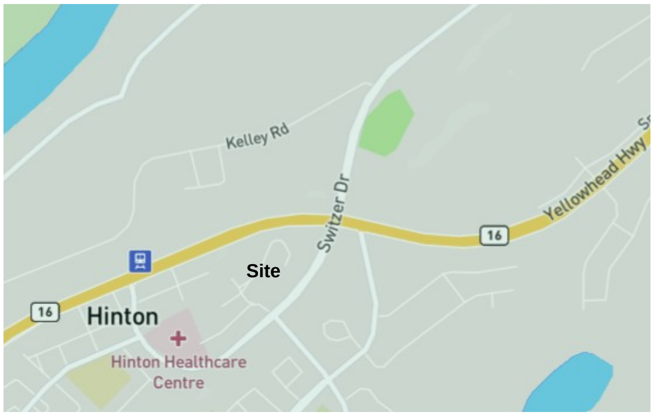

Fig. 1. Site location of the proposed Mountain View Hinton development near Yellowhead Highway and McArdell Drive, Hinton, Alberta

The parcel occupies approximately 40,510 sq. ft. and is planned for a four-storey residential apartment building containing 43 dwelling units (see Table 1 for details). The development program includes an underground parkade with 27 parking stalls, 28 surface parking stalls, bicycle storage facilities, and a landscaped amenity area oriented toward the rear ravine. The parcel benefits from direct access to a major regional transportation corridor and proximity to trails, parkland, and surrounding urban services, thereby enhancing both accessibility and development potential.

From a civil engineering perspective, the development arrangement is governed by both functional requirements and physical constraints. The parcel is characterized by irregular boundaries and variable topography, requiring the building footprint, internal circulation, and parking configuration to be planned with careful attention to grading transitions and land-use efficiency. The rear portion of the property interfaces with a natural ravine and adjacent low-lying terrain, introducing additional considerations related to slope setback, drainage routing, and the placement of retaining measures. As a result, the development configuration is more complex than that of a typical level urban parcel, since the final arrangement must balance architectural intent, vehicular access, municipal servicing, earthworks, and long-term stability within a constrained footprint.

The overall concept reflects an integrated planning approach in which building positioning, access geometry, and parking configuration are coordinated with the natural terrain. The inclusion of underground parking is particularly significant because it improves land-use efficiency and reduces surface congestion, thereby allowing a greater portion of the parcel to be allocated to circulation, landscaping, and amenity space. In addition, the project benefits from existing municipal infrastructure, including water supply, sewer and stormwater systems, and electrical service, which supports the feasibility of the proposed development. Because of the site's connection to Highway 16, the design of site access and internal vehicle movement also required consideration of transportation approval requirements and safe ingress and egress control. Collectively, these factors establish the development layout as a technically driven response to both project objectives and physical site constraints.

Fig. 2. Front elevation rendering of the proposed Mountain View Hinton development.

B. Site Constraints

The principal constraints affecting the Mountain View Hinton development arise from topography, subsurface variability, ravine adjacency, and climatic exposure. The parcel was initially undeveloped and characterized by irregular boundaries and variable ground-surface conditions. These features impose direct limitations on grading design, building placement, parking geometry, and construction staging. Unlike a level greenfield or urban infill site, the development envelope in this case must accommodate elevation transitions while maintaining adequate access, drainage performance, and compatibility with the intended residential land use.

A significant geotechnical and environmental constraint was the presence of unknown fill material identified during the initial environmental review. Fill of uncertain origin introduces risk because its composition, density, and engineering behavior may vary substantially across a site. From a geotechnical standpoint, uncontrolled or non-native fill may affect bearing performance, settlement response, excavation stability, and suitability for reuse as engineered fill [2]. From an environmental standpoint, such material may also require additional assessment to confirm compliance with applicable soil and groundwater criteria before development proceeds [1]. The need for Phase II environmental investigation and further subsurface assessment therefore reflected the importance of reducing uncertainty associated with these fill conditions [1], [2].

Another major constraint was the site's interface with a natural ravine and adjacent low-lying terrain at the rear of the property. This condition imposed additional requirements related to slope stability, runoff control, erosion protection, and the long-term performance of retaining systems. Development near a ravine is not governed solely by foundation bearing considerations; it also requires evaluation of global and local stability, drainage pathways, and the potential effects of seepage or seasonal water movement on soil behavior [2]. As a result, the site layout and structural support strategy had to account for both the immediate building footprint and the surrounding ground response over time.

The climatic setting of Hinton introduced a further layer of constraint. The region is subject to severe winter conditions, including heavy snow loads, freezing temperatures, and exposure to hail and harsh weather. These factors influence not only building-envelope design, but also site grading, surface drainage performance, freeze-thaw durability, and maintenance requirements [2], [6]. In practical terms, the site must be designed to remain functional and serviceable under both normal operating conditions and seasonal climatic extremes. Accordingly, the constraints affecting the project are multidimensional and require a coordinated engineering response rather than isolated design solutions.

TABLE I PROJECT CHARACTERISTICS USED FOR CONCEPT DEVELOPMENT

Project Type	Four-storey residential apartment
Residential Units	43 units

Parking Program	27 underground plus 28 surface
Site Area	40,510 sq ft (3,764 m^2)
Key Constraints	Ravine edge, fill, grades, winter climate

3. ENVIRONMENTAL AND GEOTECHNICAL BASIS

A. Environmental Review

A Phase I Environmental Site Assessment (ESA) was completed for the subject property at 140 McArdell Drive, Hinton, Alberta, in general accordance with CSA Z768-01 (reaffirmed 2022) and the Alberta Environmental Site Assessment Standard, December 2024 [3]. The Phase I ESA identified one Area of Potential Environmental Concern (APEC), namely unknown fill material within the subject site, with the associated Potential Contaminating Activity defined as importation of fill material of unknown quality [3]. On this basis, the Phase I ESA concluded that further investigation was warranted and recommended a Phase II ESA to assess potential impacts to soil and groundwater [3].

A Phase II ESA was subsequently undertaken in accordance with CSA Z769-00 (reaffirmed 2023) and the Alberta Environmental Site Assessment Standard, December 2024 [4]. The intrusive investigation included four boreholes, installation of groundwater monitoring wells in boreholes BH-2 to BH-4, and laboratory testing of soil and groundwater samples for petroleum hydrocarbons (PHCs), polycyclic aromatic hydrocarbons (PAHs), and volatile organic compounds (VOCs) [4]. Soil and groundwater analytical results were compared with the 2024 Alberta Tier 1 Soil and Groundwater Remediation Guidelines for residential/parkland use under coarse-grained criteria, and the reported results indicated that all analyzed parameters were below the applicable guideline values [4]. The Phase II ESA therefore concluded that no further subsurface environmental investigation was required at the time of reporting [4].

For residential developments of this type, the engineering significance of fill extends beyond demonstration of chemical compliance alone. Fill of uncertain origin may affect excavation management, material handling and reuse, groundwater interaction, drainage behavior, and the reliability of final grading works. Consequently, environmental due diligence should be closely coordinated with geotechnical assessment so that both regulatory and constructability considerations are addressed within a unified site-development framework [1], [4].

B. Subsurface Characterization

A geotechnical site investigation was undertaken to support foundation planning and assess the feasibility of the proposed multi-storey apartment development with underground parkade [5]. The field drilling program was carried out on June 24 and 25, 2025, and consisted of four boreholes, BH-1 to BH-4, drilled using solid stem augers. Boreholes BH-2 to BH-4 were advanced to 9.0 m below ground surface, while BH-1 was advanced to 6.0 m [5]. Grab samples were collected at regular depth intervals of approximately 0.75 m, and Standard Penetration Tests (SPTs) were conducted at 1.5 m intervals. In addition, three standpipe piezometers were installed in BH-2 to BH-4 to permit short-term groundwater monitoring [5].

The geotechnical report indicates that subsurface conditions generally consisted of sand and gravel fill underlain by sandstone and/or silty sand [5]. The near-surface fill layer was encountered in all boreholes and extended to depths ranging approximately from 3.2 m to 7.0 m, below which sandstone was encountered in some boreholes and silty sand in others [5]. Laboratory testing included natural moisture content determination, water-soluble sulphate testing on selected samples, and grain-size analyses [5]. The report emphasizes that soil conditions are geologically variable and may differ between borehole locations, and therefore that actual conditions should be confirmed during construction, particularly in areas of excavation [5].

In practice, subsurface characterization of this type is fundamental because it provides the technical basis for evaluating excavation behavior, bearing response, settlement potential, groundwater control requirements, and the suitability of below-grade construction such as an underground parkade [2], [5]. As emphasized in the Canadian Foundation Engineering Manual, the reliability of foundation recommendations depends directly on the adequacy of site investigation, the interpretation of subsurface variability, and the characterization of groundwater conditions [2].

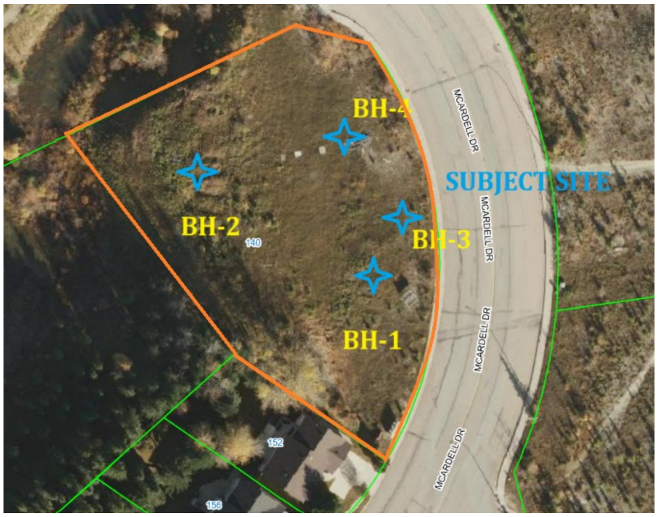

Fig. 3. Approximate borehole layout and site exploration context.

4. DESIGN CONSTRAINTS AND ENGINEERING RESPONSE

A. Ravine Interface and Drainage

A principal engineering constraint associated with the Mountain View Hinton development was the ravine-adjacent condition located at the rear of the site (Figs. 3 and 4). For developments situated near sloping ground, satisfactory performance is governed not only by the bearing resistance of the foundation materials beneath the structure, but also by the stability of the adjacent soil mass, the prevailing groundwater regime, and the influence of surface runoff and erosion processes. In such settings, the design problem extends beyond local foundation support and must consider global slope stability, seepage conditions, and long-term serviceability of both the building platform and the surrounding terrain [2].

Project reports indicate that the development incorporated retaining measures and drainage controls in response to these site conditions. The project article describes mechanically stabilized earth (MSE) retaining walls, concrete retaining elements, and controlled drainage systems at the ravine interface, while the geotechnical report includes recommendations for subsurface drainage, lateral earth pressure, basement development, and excavation-related groundwater control [5]. This response is consistent with established geotechnical practice because retaining structures perform more reliably when structural restraint and hydraulic control are addressed concurrently [2]. In practical terms, the performance of an earth-retaining system depends not only on its ability to resist lateral earth pressures, but also on its capacity to limit hydrostatic pressure buildup behind the wall. Accordingly, the use of free-draining backfill, subdrainage, surface collection systems, and controlled discharge points is essential for maintaining long-term wall stability, reducing deformation, and preserving the overall stability of the retained ground [2], [5].

Fig. 4. Rear site condition showing slope transition toward the ravine and adjacent low-lying area.

This approach is consistent with conventional limit equilibrium analysis, in which slope stability is assessed by comparing resisting and driving forces along a potential failure surface [2]. Even where a retaining wall remains structurally adequate, inadequate drainage may increase groundwater pressures, reduce effective stress, diminish available shear strength, and lower the factor of safety of the surrounding slope system [2]. The ravine interface therefore required a composite stabilization strategy in which retaining measures, grading control, and drainage management were integrated to support both immediate constructability and long-term site performance.

B. Unknown Fill and Layout Optimization

A second major constraint was the presence of unknown or non-native fill identified during the environmental and subsurface review. The Phase I ESA identified one Area of Potential Environmental Concern (APEC), namely unknown fill material within the subject site, and recommended further investigation [3]. The subsequent Phase II ESA confirmed that the intrusive investigation was directed specifically at this fill-related concern through borehole drilling, groundwater monitoring, and laboratory assessment of soil and groundwater samples [4]. Fill of uncertain origin presents a significant challenge in both geotechnical and environmental terms because its composition, density, placement history, and engineering behavior are commonly variable. From a geotechnical perspective, uncontrolled fill may exhibit inconsistent stiffness, nonuniform drainage behavior, unpredictable settlement characteristics, and variable bearing response [2]. Where such material includes construction debris or poorly compacted zones, the potential for differential settlement increases, particularly beneath pavements, shallow foundations, slabs-on-grade, and retaining structures [2].

Fig. 5. Existing site conditions illustrated uneven surface grades and areas of apparent fill.

The engineering implications of fill extend beyond mechanical performance. Alberta's Tier 2 contaminated-site framework recognizes that site-specific conditions, including fill characteristics, groundwater pathways, and land-use sensitivity, may necessitate a level of technical assessment beyond that provided by generic assumptions [1]. In practice, the presence of fill may influence excavation management, material classification, reuse potential, groundwater interaction, and confidence in the final grading platform. For residential developments, where serviceability requirements and long-term performance expectations are relatively demanding, it is necessary to evaluate both the chemical suitability and the mechanical acceptability of such materials [1], [2]. The site therefore required coordinated environmental and geotechnical interpretation rather than separate assessment of regulatory compliance and foundation support conditions.

This coordinated interpretation is reflected in the project reports. The Phase II ESA described near-surface sand and gravel fill and concluded that PHCs, PAHs, and VOCs in both soil and groundwater were below the applicable 2024 Alberta Tier 1 residential/parkland coarse-grained criteria, with no further subsurface environmental investigation recommended at that time [4]. The geotechnical report likewise identified sand and gravel fill across all boreholes and advised that fill thickness may vary significantly across the site, such that additional test pits or hand-augered holes may be required for more accurate stripping-volume determination and that footing support should extend below the fill layer [5]. Taken together, these findings indicate that the fill condition was both an environmental due-diligence issue and a geotechnical design issue.

Rather than treating the fill solely as a construction impediment, the project incorporated the excavation requirement into a broader site-optimization strategy by transitioning from a surface-parking-dominated concept to one that included an underground parkade. This response is technically rational because the need to remove or manage unsuitable near-surface materials may be used to create permanent below-grade functional space, thereby improving development efficiency. From a site-planning and engineering standpoint, the underground parkade offers several advantages: it reduces the portion of the site occupied by surface parking, permits more efficient use of the parcel for circulation and amenity purposes, and integrates excavation-related works into the permanent development scheme. It also allows closer coordination among the structural, geotechnical, and construction teams with respect to excavation depth, support requirements, groundwater control, dewatering, and retained-earth design [2], [5].

This response is consistent with the broader guidance of the Canadian Foundation Engineering Manual, which emphasizes that site investigation results should inform not only foundation selection, but also excavation planning, groundwater management, retaining systems, and constructability [2]. In this sense, the final layout represents a design adaptation in which a subsurface constraint was converted into a development advantage through coordinated engineering decision-making.

C. Cold-Climate Durability and Fire-Resilient Response

The climatic setting of Hinton imposed a significant design constraint affecting both structural performance and long-term envelope durability. The region is subject to prolonged freezing temperatures, seasonal snow accumulation, freeze-thaw cycling, hail exposure, and severe weather, all of which influence roof behavior, moisture migration, thermal performance, and maintenance demand. Accordingly, the building response should be understood as part of an integrated engineering strategy intended to address durability, occupant safety, and life-cycle performance.

From a structural and enclosure-performance perspective, the adoption of a steep roof profile is consistent with cold-region design practice because roof geometry governs snow retention, snow shedding, localized drift formation, and drainage behavior during melt periods. A steeper roof slope may reduce the duration of snow retention and improve runoff during thaw cycles, thereby limiting the risk of ice accumulation and localized ponding. The building envelope strategy is similarly important. Triple-pane glazing and a high-performance wall assembly improve effective thermal resistance and reduce conductive heat loss through the enclosure. In building-science terms, these measures improve hygrothermal performance by limiting cold-surface conditions that may lead to interstitial or interior-surface condensation. National Research Council Canada guidance and the National Building Code of Canada identify heat transfer, air leakage, and condensation control as fundamental aspects of compliant and durable wall-system performance [6].

The use of durable exterior cladding is also technically significant in a mountain-influenced environment. Repeated freeze-thaw cycles, wind-driven precipitation, hail, and thermal movement place sustained demand on the building exterior. Where cladding is supported by appropriate flashings, drainage layers, and drained or ventilated cavity detailing, the wall assembly is better able to resist water ingress, accommodate drying, and preserve the integrity of structural and insulation components [6]. This is important not only for thermal efficiency, but also for long-term serviceability, since envelope deterioration in multi-storey residential construction may lead to moisture damage, reduced insulation effectiveness, and increased maintenance demand. NRC guidance further emphasizes that wall-system performance is closely linked to thermal resistance, airtightness, and condensation resistance [6].

The use of non-combustible exterior materials may also be justified as a resilience-oriented design measure for a project located within a region that is seasonally exposed to wildfire risk. In this context, the selection of non-combustible cladding and related exterior components may reduce ignition susceptibility and improve the robustness of the building envelope under external fire exposure. However, in the absence of a project-specific wildfire hazard assessment, local bylaw requirement, or authority-mandated fire-resilience criterion, this rationale is best presented as a resilience consideration supplementary to the primary cold-climate and durability objectives of the envelope design.

The cold-climate response also extends to the site and lower envelope. Freeze-thaw action may affect entrance slabs, paved areas, shallow drainage infrastructure, and the seasonal response of near-surface fill materials [2], [6]. Consequently, grading and drainage must be configured to minimize ponding, control infiltration near the foundation, and maintain positive runoff under both thaw events and rainfall conditions. Considered collectively, the selected roof form, glazing system, cladding durability, thermal envelope, and non-combustible exterior materials (Fig. 6) represent a unified durability strategy in which thermal control, moisture management, and environmental exposure resistance are treated as interdependent engineering objectives [2], [6].

Fig. 6. Climate-responsive architectural rendering.

5. DISCUSSION

This case study highlights the value of integrating environmental and geotechnical investigations early in the design process. Once unknown fill was identified during the environmental review, the project required evaluation of both chemical suitability and geotechnical constructability rather than separate treatment of these issues [1], [3], [4]. That integrated approach provided a stronger basis for grading decisions, excavation planning, material management, and coordination between subsurface conditions and the final development layout [2], [4], [5].

The project also demonstrates the importance of designing for both immediate stability and long-term serviceability. In this case, retaining measures, drainage systems, parking configuration, and building-envelope decisions all contributed to the overall performance of the proposed development [2], [5], [6]. For sites in foothill and mountain-interface settings such as Hinton, technical success depends on recognizing that subsurface conditions, slope constraints, climatic exposure, and access requirements are interdependent rather than isolated design variables. The engineering significance of the project therefore lies not in any single design feature, but in the coordinated response developed across environmental, geotechnical, civil, and building-envelope considerations.

6. CONCLUSION

Mountain View Hinton represents a practical case study in integrated civil engineering for residential development on a constrained site. The project required coordinated assessment of environmental conditions, subsurface variability, ravine-edge stability, drainage control, access planning, and cold-climate durability in support of a multi-storey residential building with underground parking [3]–[6]. The case demonstrates that technical risks associated with unknown fill, topographic relief, groundwater-related constraints, and severe climatic exposure can be managed more effectively when site investigation findings are incorporated into planning and design from the outset [1], [2].

More broadly, the project illustrates that successful development on complex sites depends on early integration of environmental due diligence, borehole-based subsurface characterization, retaining and drainage strategies, and durability-oriented building response. This integrated approach improves constructability, supports regulatory and technical decision-making, and provides a more reliable basis for long-term serviceability of the completed development.

DATA AVAILABILITY STATEMENT

Some data that support the findings of this study are contained within project-specific environmental and geotechnical reports cited in this paper. Additional project information is proprietary or confidential in nature and may only be provided with restrictions. Requests for non-public supporting materials may be directed to the corresponding author and will be considered subject to client and project-permission requirements.

ACKNOWLEDGMENT

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Note: Figures derived from project visuals are included for illustrative support of the case study and are not used as primary technical sources.

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A study on the design and implementation challenges of an aircraft hangar at Shah Amanat International Airport, Chittagong, Bangladesh

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ABSTRACT: A pre-engineered steel frame structure (PEB) is an economical and time-saving solution for industrial applications. This case study is a comprehensive analysis of the construction of a long-span aircraft hangar (a PEB) in Shah Amanat International Airport, Chittagong, Bangladesh. There were many engineering challenges to overcome during the project, from planning to implementation. For example, the design of a long-span building, the clearance and height constraints and a complicated erection technique. The paper explains these matters and provides appropriate solutions according to the codes and guidelines. The design and analysis of this project have been carried out using STAAD PRO software.

1. INTRODUCTION

The need for industrial steel buildings, especially pre-engineered steel structures, is increasing rapidly over time in several sectors [1]. Steel is a major construction material in civil engineering and is generally preferred over concrete [2]. Steel offers several advantages over concrete. Steel provides more structural strength, enabling vast open floor space for high efficiency in operation, can be built in much less time than reinforced concrete structures, has a longer lifespan and can be reused [3]. These advantages have led to a significant increase in the usage of steel structures in industrial warehouses, storage units, pedestrian bridges, workshops, commercial buildings, aviation hangars, manufacturing and assembly facilities, etc. [4].

However, challenges arise in the design and implementation of such structures based on the specific demands of the project and geographical limitations [5]. Achieving a design that is optimized for structural integrity while also being cost-efficient can sometimes prove to be difficult [6]. Steel components and elements must be designed in a manner that allows for transport to the construction site, as well as be compatible with existing technologies for implementation.

This paper focuses on such challenges encountered in the design and implementation phase of an aircraft hangar as well as their solutions. Aircraft hangars differ significantly from conventional buildings due to their requirement for large unobstructed spaces that facilitate aircraft movement and maintenance operations. In this project, the primary constraint during the design phase was maintaining a particular clear height with a defined maximum ridge height. A specific, clear height was essential to accommodate the entry of aircraft into the hangar. Additionally, the shear force in the primary design was substantially higher compared to the column capacity. In the implementation stage, the heavy-duty nature of the structure made it difficult to achieve proper weld penetration while maintaining structural integrity. Another challenge was the safe transportation and handling of heavy L-shaped columns, which could not be accomplished with the use of conventional trucks. The most critical part of implementation was the installation of the prefabricated members while preventing any sagging of the rafters or lateral movement of the columns. Addressing these issues demanded attention to detail and caution in engineering planning at both the design stage and the implementation stage. Therefore, this study may serve as a framework for the design and implementation of future projects of a similar nature.

2. PROJECT OVERVIEW

The project has been undertaken with the aim of constructing an aviation facility for CASA-235 aircraft. The free span of the hangar shed is 55.4580 m. There are two adjoining steel buildings of 7.8650 m width on both sides of the shed. The hangar shed consists of ten frames in total, which adds up to the total length of 52.2120 m. Fig. 1 presents the plan view of the project.

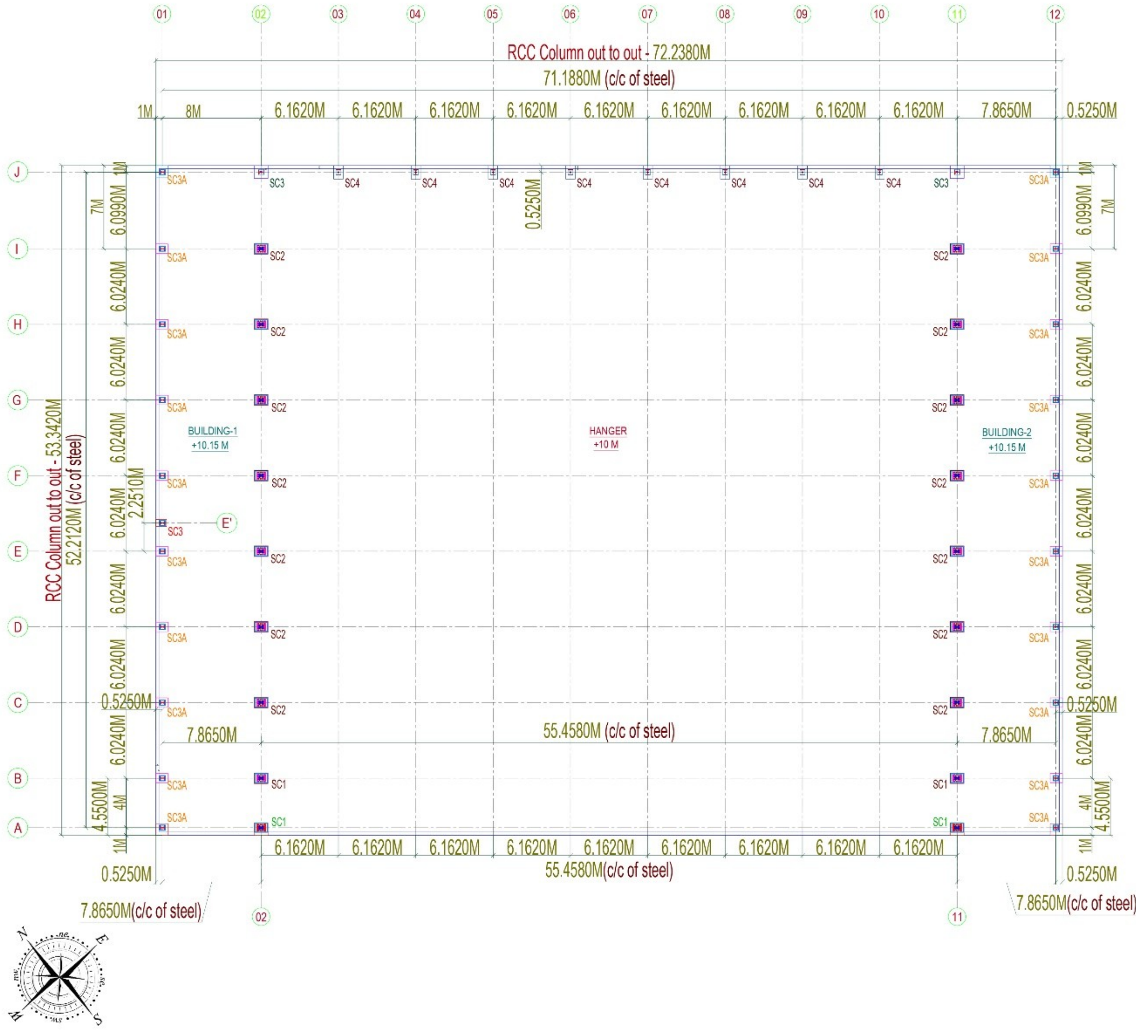

Fig. 1 General plan of the shed and office buildings

The ridge height of the hanger shed is 9.83 m, and the eave height is 7.24 m. Fig. 2 and Fig. 3 show the elevation view of typical sections of the project.

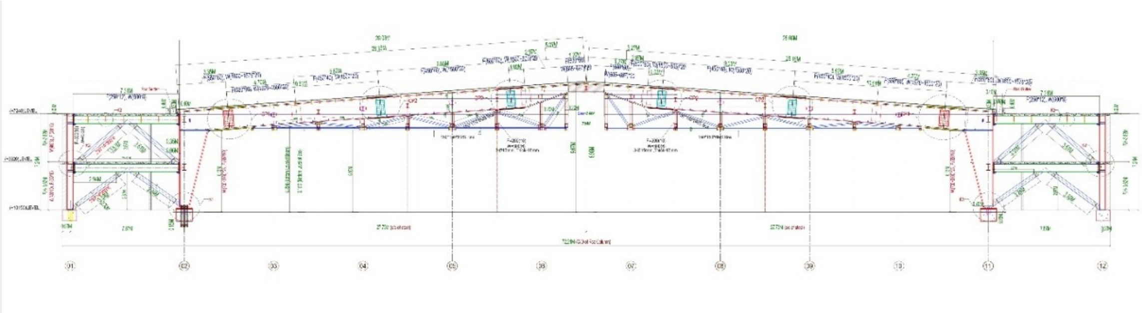

Fig. 2 Elevation of frame A and frame B

Fig. 3 Elevation of frame D to frame I

Each frame consists of a solid-web portal frame system except for the first two frames. The first two frames of the hangar shed utilize a combination of truss-rafter portal frame system. All the frames are supported by one steel column on each side. The end frame is supported by eight additional steel columns. The adjoining steel buildings has an equal number of frames with two decking floors.

The project site is in Chittagong, Bangladesh, which is a coastal region. Fig. 4 illustrates the actual status of this project after successful completion.

Fig. 4 Aircraft hangar shed after completion

3. DESIGN CODES & ASSUMPTIONS

The design of this aircraft hangar shed adheres to several design codes, as represented in Table 1. Assumptions were made as per the instructions of the codes for pre-engineered steel structures.

Table 1 Codes used in design

Area of application	**Code name**
Design and analysis code	AISC LRFD 2001
Wind load	BNBC 2006
Seismic code	UBC 94
Design load	BNBC 2006
Purlin design	AISI-LRFD 96

4. FABRICATION MATERIALS

The strength and specifications for materials used for the fabrication of structural elements are presented in **Table 2**.

Table 2 Specification of materials

Structural Components	Specifications	Strength (psi)	Grade
Built-up Column & Beam section (I section)	ASTM A572	F_y = 50,000	50
Built-up Rafter section (I section)	ASTM A572	F_y = 50,000	50
C section G.I purlin	ASTM A653	F_y = 50,000	50
0.50mm Zinc Alum Color Sheet. Origin: Sysco, Taiwan	ASTM A792 GR 550 MPa, AZ150 gm/m²	F_y = 80,000	80
M.S Angle, M.S Pipe, MS Box	ASTM A36	F_y = 36,000	36
Connection bolt	DIN 933, Grade 8.8	F_u = 800 MPa	8.8
MS Anchor bolt	ASTM F1554	F_y = 36,000	36
0.70 mm thick decking sheet	ASTM A653	F_y = 50,000	50

5. DESIGN PROCESS & PRINCIPLES

STAAD.PRO v.8i software has been used to design and analyze the frame components of this aircraft hangar shed. First, the model was drawn with appropriate dimensions. Next, various loads were assigned to the frames. After that analysis of the completed model was conducted. Verification for errors, modification of member properties, and reiteration of analysis were done until the requisite level of accuracy and structural integrity was attained. **Fig. 5** shows the 3D model of the shed in STAAD.PRO.

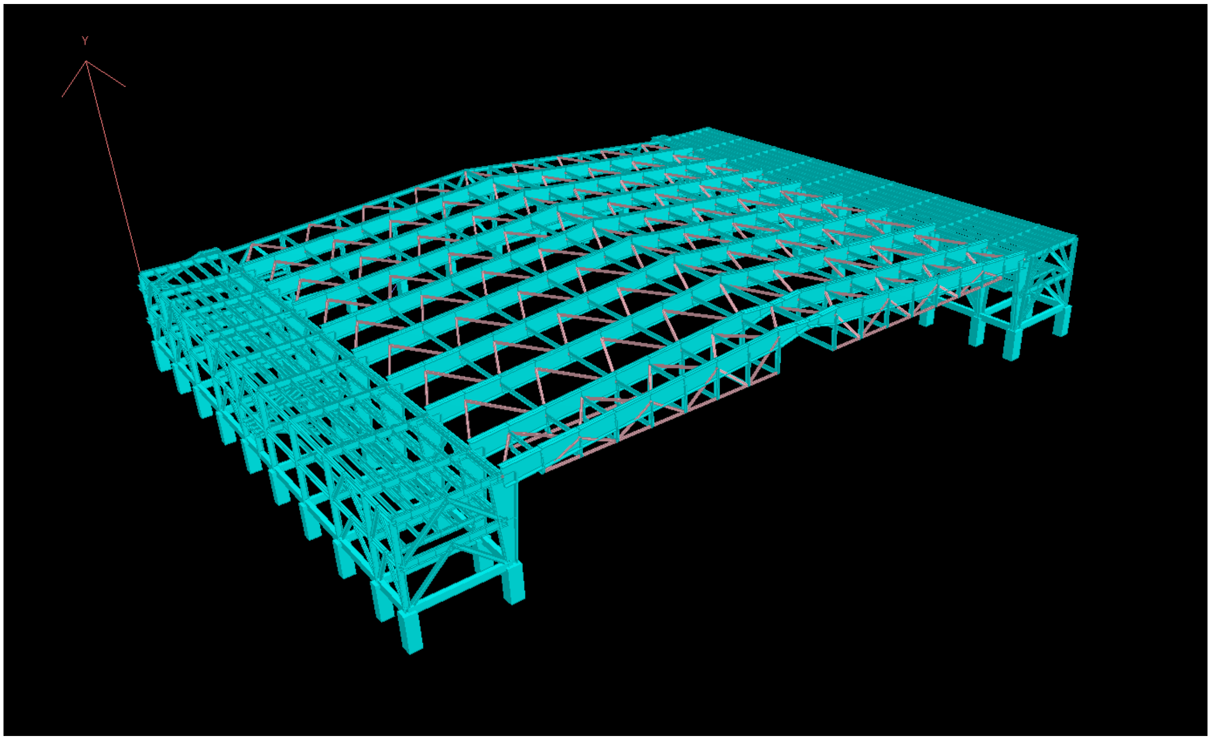

Fig. 5 STAAD.PRO model for aircraft hangar shed

6. DESIGN PHASE

The maximum height of the hanger shed needed to be kept under 9.7536 m. This restriction was imposed on the shed, designated for construction at an airport, to ensure clear passage for the transmission of navigational and radar signals. Additionally, this requirement sets a limit on the usable clear height for the aircraft. This limitation is because the hangar shed needed to have a lengthy free span. To attain this lengthy free span, it was necessary to utilise heavier sections, which led to significant deflection of the rafter members due to their own weight. In order to maximize the clear height within the imposed limitation, a technique named 'camber' was adopted in the design of the rafters. The application of cambering allowed the model's design to have an additional 76.4 mm ridge height instead of being restricted to 9.7536 m. Consequently, the maximum clear height is utilized while accounting for the deflection induced by the gravity load. The extra 76.4 mm also facilitated the implementation of a steeper slope for improved drainage and guaranteed the absence of ponding on the roof due to deflection. **Fig. 6** and **Fig. 7** show the value of dead load and roof live load acting on frame C. **Fig. 8** and **Fig. 9** illustrate the deflected shape of frame C resulting from dead load and gravity load, respectively, at the ridge. **Table 1** represents the maximum deflection at the ridge resulting from these loads.

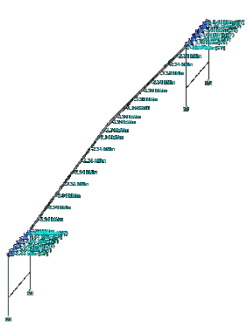

Fig. 6 Dead load acting on frame C

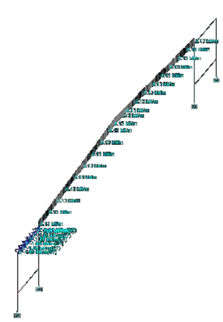

Fig. 7 Roof live load acting on frame C

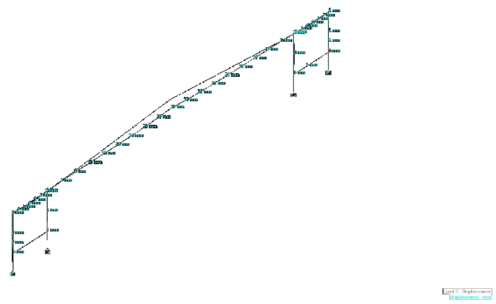

Fig. 8 Vertical deflection due to dead load on frame C

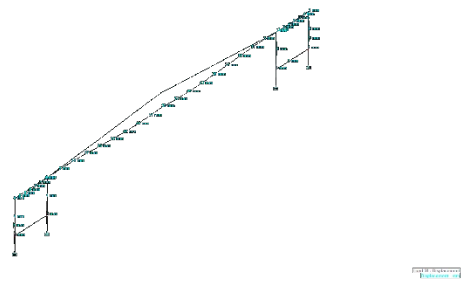

Fig. 9 Vertical deflection due to gravity load on frame C

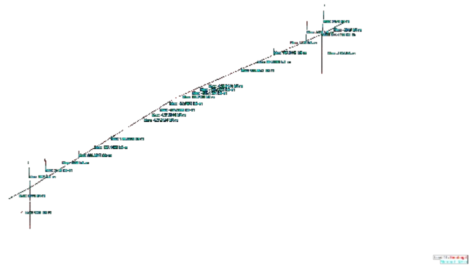

Fig. 10 Bending moment at frame B

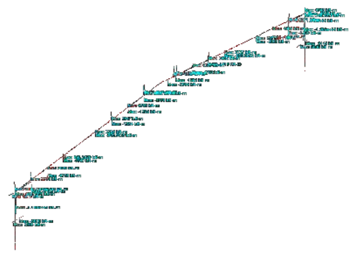

Fig. 11 Bending moment at frame C

Table 3 Deflection due to dead load, roof live load and gravity load

Load	Maximum Vertical Deflection (mm)
Dead Load	51
Roof Live Load	30
Gravity Load	82

Although the front section of the aircraft can be positioned easily inside the hangar, the aircraft's empennage posed an additional challenge. The tapered I-section utilized around the ridge has a web-depth of 1500–1800 mm. Thus, the clear height at that region of the shed becomes 7.87 m. However, an extra 1.11 m of clearance was required to accommodate the aircraft's empennage. To resolve this issue, the depth of the rafter web was reduced to 697 mm. A hinge connection was incorporated at the ridge to ensure that no moment is generated since the decreased depth diminishes the load-bearing capacity of the rafter section. In the first two frames, a truss system was integrated with the I-section to compensate for the reduced depth of the rafter. These two frames were interconnected using a truss system to operate as a unified system. Hence, the first two frames were able to accommodate the design loads without exceeding the allowable deflection or experiencing failure. For the same reason as above, an additional 10 mm of thickness was added to the flange thickness of supporting columns in these frames. design considerations ensured structural integrity while providing an additional 177.8 mm of unobstructed room for the aircraft's empennage inside the hangar. **Fig. 10** and **Fig. 11** illustrate that the inclusion of a hinge in the initial two frames makes the moment at the ridge zero, whereas the moment progressively increases toward the support, in contrast to the other frames. **Fig. 12** shows an actual condition of the shed when aircraft enters the hangar shed.

Fig. 12 Aircraft inside the hangar shed during operational stage

The next major challenge during the design process was addressing inadequate shear capacity. The loads imposed on the structure produced a shear force substantially higher than the structure's capacity to withstand shear without failure. The inadequate shear capacity resulted in structural instability of the initial model. To resolve this issue, certain adjustments were implemented in the design of this aircraft hangar.

The first step involved modifying the layout of two office complexes within the aircraft hangar shed. The two-story office buildings on both sides of the shed were primarily positioned inside of the shed. In order to enhance shear capacity, the office buildings were now connected with the external section of the hanger shed. This integrated system exhibited a significantly greater moment of inertia compared to the previous design. The increase in the moment of inertia enabled the structure to withstand significantly higher lateral forces. Both offices building greatly affect the structural integrity of the model. **Fig. 13** shows the amount of shear force generated in the Y direction in the model. **Fig. 14** represents the same comparison for shear force in the Z direction.

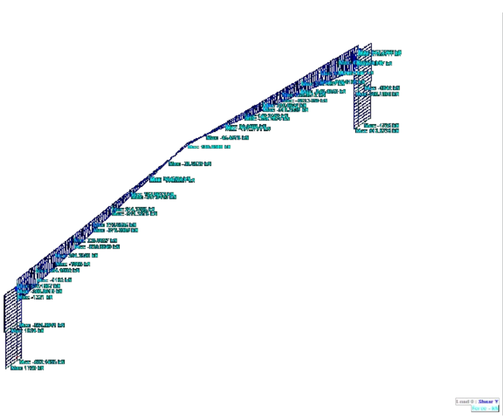

Fig. 13 Shear force acting in Y direction on frame C

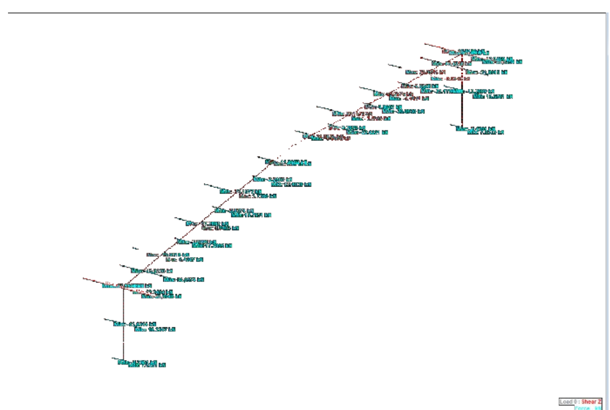

Fig. 14 Shear force acting in Z direction on frame C

The next step was the incorporation of shear keys into the base plates of the steel columns supporting the hangar shed. The anchor bolt's capacity in the base plate design was insufficient to withstand the applied shear force. The H-shaped shear keys provided with additional surface area to effectively transfer shear from the steel column base to the foundation and subsequently into the surrounding ground. **Fig. 15** and **Fig. 16** show the configuration of baseplate design incorporating both anchor bolts and shear keys.

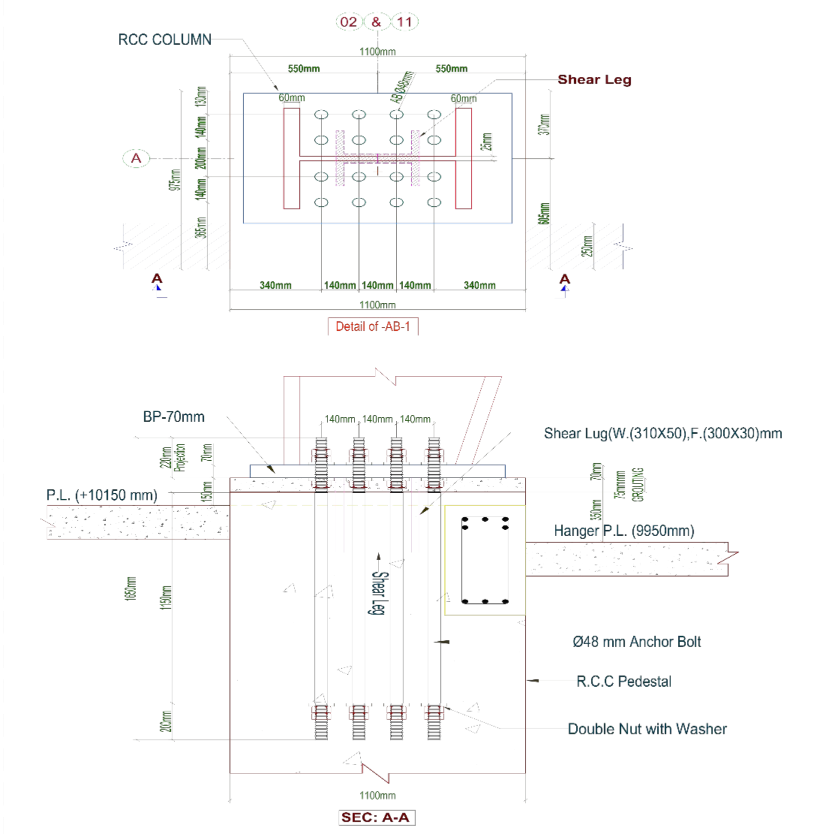

Fig. 15 Detail of anchor bolt (AB – 1)

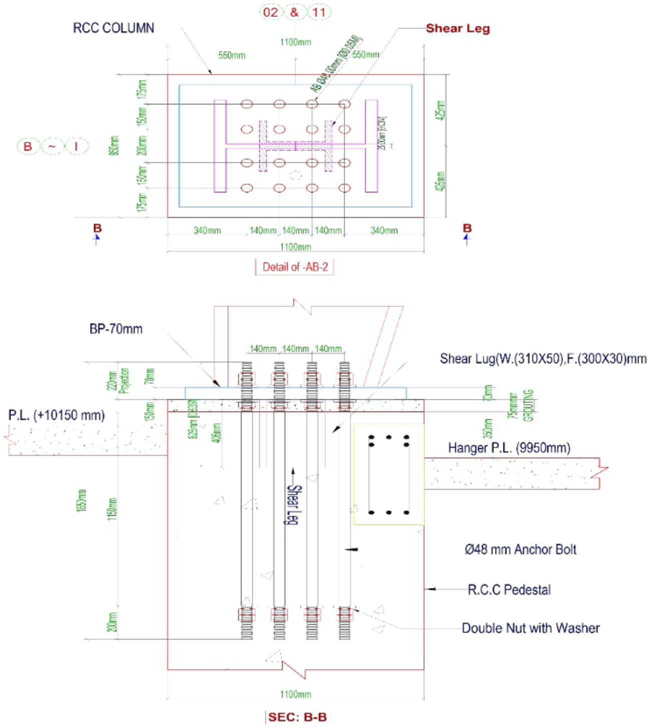

Fig. 16 Detail of anchor bolt (AB – 2)

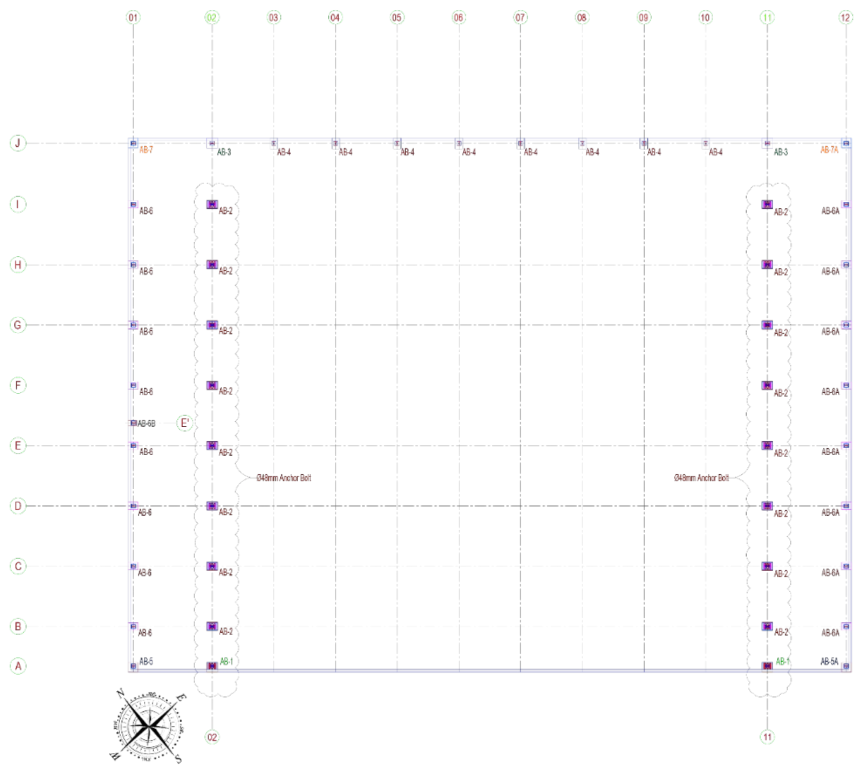

Fig. 17 Anchor bolt layout plan

Fig. 17 shows the anchor bolt layout plan of the project. These two design changes greatly enhanced the hanger shed's structural integrity and resistance to lateral forces.

7. IMPLEMENTATION PHASE

Upon the completion of the structural design, the first challenge encountered was the precise fabrication of the designed members. The fabrication process involved the production of large built-up sections using MS plates with a thickness between 25 and 50 mm. The joining of thick plates required proper weld penetration across the full thickness of the plates. To ensure full penetration butt welding of thick plates, multiple-pass welding procedures were adopted under strict quality control measures. Furthermore, accuracy of the whole fabrication process was ensured by conducting a full-scale mock-up assembly of the primary rafters and columns at the factory. Thus, the possibility of any problem regarding alignment, structural geometry, welding distortion, or joint fit-up was eliminated.

Following the successful fabrication of all designed components, the next issue was the safe conveyance of these prefabricated steel elements to the construction site. The columns of the hangar shed had an atypical L-shape, each weighing around 9 tons. Specialized trailers were employed for providing safe transportation due to the unconventional design, rendering conventional trucks unfeasible. Transportation was conducted during low-traffic hours. Upon arrival at the project site, all the structural members were unloaded using 50-ton and 25-ton mobile cranes in accordance with approved lifting plans and safety regulations.

The most critical problem emerged thereafter during the erection stage. The construction of a large clear span without internal supports could easily cause the rafter members to sag or the column sections to deflect. Since the construction site was coastal, substantial wind load also contributed to the associated risks. To resolve this problem, the two-story office buildings were erected first, followed by the commencement of the primary hangar's construction. **Fig. 18** shows the installation of L-shaped columns after the erection of office buildings. An outward offset of approximately 8 mm was provided at the columns to compensate for the anticipated deflection under the self-weight of the rafter. **Fig. 19** shows the connection process of rafters with L-shaped columns.

Fig. 18 Erection of office buildings and L-shaped columns of the shed

Fig. 19 Installation of the connection between the rafter and the L-shaped column

To safely perform the lifting operation, a total of five cranes were employed: one 100-ton crane at the center, two 50-ton cranes at both sides, one 25-ton crane, and one 12-ton crane, which is shown in **Fig. 20**.

Fig. 20 Cranes used in lifting operation

To prevent sagging during erection, seven temporary I-section supports were placed beneath each rafter and retained until the permanent bracing and purlin systems were completed. After the structural system was fully completed, all temporary supports were systematically removed following technical confirmation of structural stability. Thus, the erection process was successfully completed.

8. RESULTS AND DISCUSSIONS

The design and implementation of the aircraft hangar project was done successfully within the approved duration while maintaining the required quality standards. The hangar shed would provide adequate space for aircraft maintenance and long-term structural stability. **Table 4** represents a summary of maximum shear force, bending moment, and displacement encountered in the final design of the hangar shed. **Table 5** shows the estimated quantity of steel that was required for the successful implementation of the designed shed.

Table 4 Summary of software analysis

Direction	Maximum displacement (mm)	Maximum shear force (KN)	Maximum bending moment (KN-m)
X – axis	-11	-3641	-93
Y – axis	-82	-1842	-978

Z - axis	449	674	1231

Table 5 Summary of the required steel quantity in MT

Supplied Items	**Quantity**
Build up I section Column, rafter, Beam, Sub-beam, Box Bracing, Base Plate	1,340
Galvanized nut bolt with washer.	34
Purlin & Grit	52
Stress bar & sag rod	4
0.47 mm thick zinc alum profile sheet for Roof and wall sheeting	21
Anchor Bolt	11
0.70mm mm thick Galvanized Decking Sheet	26
Total Quantity of Steel Obtained	1,488

9. CONCLUSION

The design and analysis in this study efficiently address unique challenges such as allocation for aircraft clearance requirements, compliance with shed height restrictions, and structural issues associated with a large span. In addition, the study represents solutions regarding the successful implementation of the project. This project is a significant accomplishment in the domain of steel structure construction in Bangladesh. The successful execution of the project was ensured by innovative design solutions, meticulous planning, quality control, and safety management.

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Seismic Performance and Modeling of RC Frames Infilled with Sustainable Sandcrete and AAC Masonry Systems: Experimental Investigation

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ABSTRACT: Bangladesh's rapid urbanization and increasing seismic vulnerability necessitate resilient and sustainable construction systems. Sandcrete (SC) and autoclaved aerated concrete (AAC) blocks are emerging alternatives to conventional masonry due to their reduced weight and environmental benefits. However, their structural interaction within reinforced concrete (RC) frames under cyclic and dynamic loading remains inadequately understood. This study evaluates the seismic performance of RC frames infilled with SC and AAC masonry through integrated experimental and analytical approaches. Material characterization, pseudo-static cyclic tests, and shake-table experiments are conducted to assess strength, stiffness degradation, energy dissipation, and failure mechanisms. A simplified nonlinear rheology-based model is developed and calibrated using experimental data. Results demonstrate distinct behavioral differences between SC and AAC systems and highlight the importance of incorporating material-specific properties in design. The study provides performance-based recommendations for safe and sustainable application of masonry infill systems.

1. Introduction

Bangladesh's rapid urbanization and increasing seismic vulnerability demand structurally resilient, resource-efficient, and scientifically validated construction systems. Sustainable construction materials are increasingly adopted in reinforced concrete (RC) frame buildings to reduce environmental impact and construction costs (El-Kholy et al., 2026, Mukhlis et al., 2024). Sandcrete (SC) and autoclaved aerated concrete (AAC) blocks represent promising alternatives to conventional burnt clay masonry due to their lower embodied energy, reduced weight, and improved thermal performance (Gupta et al., 2022, Mukhlis et al., 2024). However, their structural interaction within RC frame systems under cyclic and dynamic loading remains inadequately quantified, limiting their safe and performance-based application in civil infrastructure (Mukhlis et al., 2024, Mainstone, 1971,Smith 1966). Moreover, most existing analytical models for masonry infilled RC frames are based on either simplified equivalent strut concepts or complex multi-strut macro-models (Asteris et al., 2017, Smith 1966). While such models can reproduce certain aspects of hysteretic behavior, many rely heavily on empirically calibrated parameters and are rarely grounded in experimentally measured material properties (Crisafulli 1997,Smith 1966). Furthermore, international guidelines increasingly emphasize performance-based seismic assessment of civil infrastructure (ASCE/SEI 41-17, 2017). The study aims to: i) experimentally characterize the mechanical, physical, and constitutive properties of sandcrete (SC) and AAC masonry systems and associated materials to establish reliable engineering parameters; ii) develop and validate nonlinear constitutive and rheological models incorporating material nonlinearity and foundation flexibility; iii) experimentally evaluate the structural performance of RC frames infilled with SC and AAC under pseudo-static cyclic and dynamic loading; and iv) calibrate and validate analytical models using experimental data for predictive structural assessment. This study evaluates the structural performance of RC frames infilled with SC and AAC through integrated experimental and analytical approaches. Material characterization (Phase I) and pseudo-static cyclic testing (Phase II) have been completed, while nonlinear modeling (Phase III) and model validation (Phase IV) are ongoing. This paper presents some experimental results from Phase II (pseudo-static cyclic testing), supported by material characterization (Phase I).

2. Materials and Methods

2.1 Material Characterization

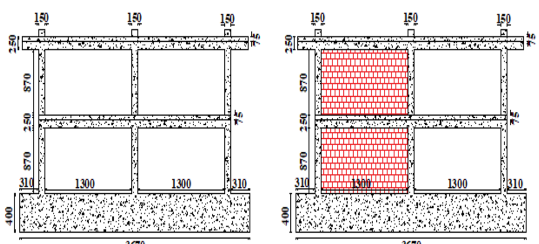
Mechanical properties of SC and AAC masonry systems were determined through experimental testing. The tests included compression, tensile splitting, and diagonal shear tests on masonry units and prisms. Key parameters obtained include compressive strength, elastic modulus, shear bond strength, and strain characteristics. AAC masonry exhibited lower density and stiffness compared to SC masonry, while SC systems demonstrated higher strength but greater variability in material properties.

2.2 Experimental Program

The experimental study was carried out for several 1:3 scale two-story two-bay RC frame specimens as shown in Fig. 1, bare/ partially infilled with SC and AAC blocks. Pseudo-static cyclic tests were conducted using displacement-controlled loading protocols to capture hysteresis behavior. Instrumentation included load cells, displacement transducers, strain gauges, and accelerometers. The fully bare RC frame was used as a reference frame to study the effect of burnt and unburnt masonry infills on the structural behavior of the RC frame. On the other hand, the infilled test specimens were fully infilled on the left panels and remaining bare on the right panels of both stories. Table 1 shows the details of structural members of the test specimens.

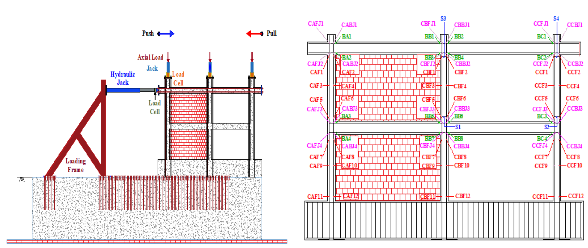
Table 1: Geometric details of structural components of test specimens (All dimensions are in mm)

Components	Sectional dimension (mm)	Longitudinal rebar (mm)	Transverse rebar(mm)
Column	150×150	4-10ϕ	ϕ8@100c/c
Beam	150×250	6-12ϕ	ϕ8@100c/c
Base	450×400	12-12ϕ	ϕ6@75c/c



(a) Bare frame (b) Infilled frame

Figure 1: Geometry of test specimens



(a) Experimental setup (b) Strain gauge locations

Figure 2: Experimental setup and instrumentation layout

3. RESULTS AND DISCUSSION

3.1 Structural Response

Both SC and AAC infill systems significantly increased the lateral stiffness and strength of RC frames compared to the bare frame. SC infilled frames exhibited higher initial stiffness and peak strength, while AAC infilled frames showed greater deformability. The bare frame specimen (2S2B_BRCF) demonstrated low lateral resistance (62.7 kN at 1.44% drift) with stable hysteretic behavior up to 3% drift, indicating ductile response. In contrast, the burnt brick infilled frame (2S2B_BCB_IRCF) showed significantly higher strength (116.7 kN) but failed in a brittle manner at about 1.65% drift. The unburnt block infilled frame (2S2B_USB_IRCF) exhibited intermediate strength (105 kN) with improved displacement capacity compared to the burnt brick system. Although a strength drop occurred after peak loading, the specimen maintained better deformability due to higher compressive capacity observed in material tests.

3.2 Stiffness Degradation and Energy Dissipation

Cyclic test results showed progressive stiffness degradation in both systems. SC infills exhibited higher energy dissipation due to stronger bonding, while AAC systems showed pinching behavior and reduced hysteretic energy. Hysteretic responses (Figure 2) were used to evaluate stiffness degradation (Figure 3), energy dissipation (Figure 4) and equivalent viscous damping ratio, based on mean values from both loading directions. The burnt brick infilled specimen showed brittle post-peak degradation and failed at an ultimate drift of about 1.65%. In contrast, the SC infilled specimen demonstrated significantly higher ductility (about 1.6 times) (Figure 2) and reached an ultimate drift of 3.0%, indicating superior displacement capacity and improved seismic performance.

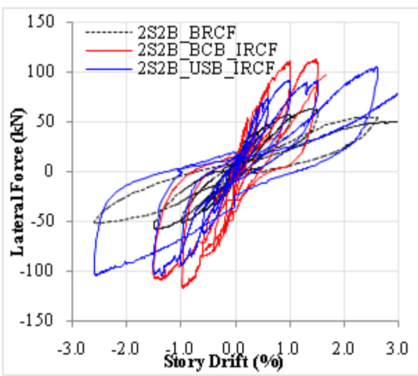


Figure 2: Lateral force- story drift curves of three specimens

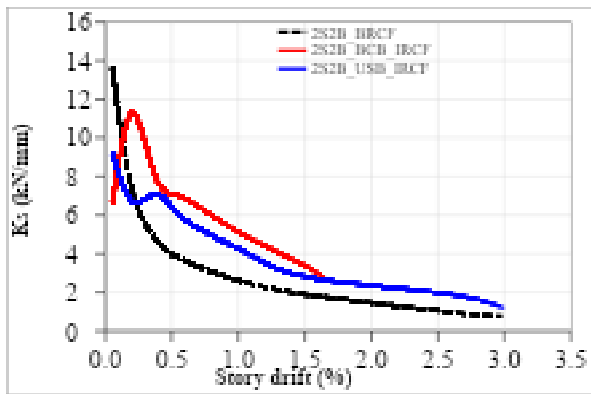


Figure 3: Stiffness degradation of three specimens

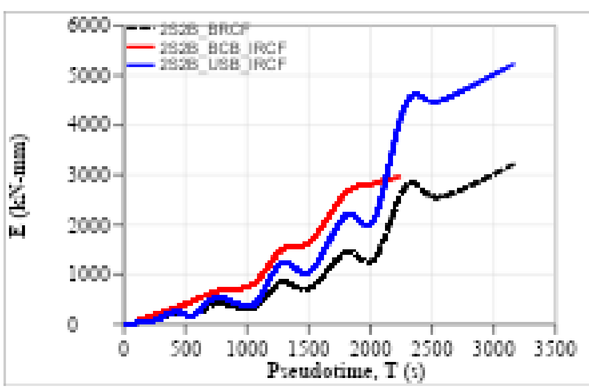


Figure 4: Cumulative energy dissipation of three specimens

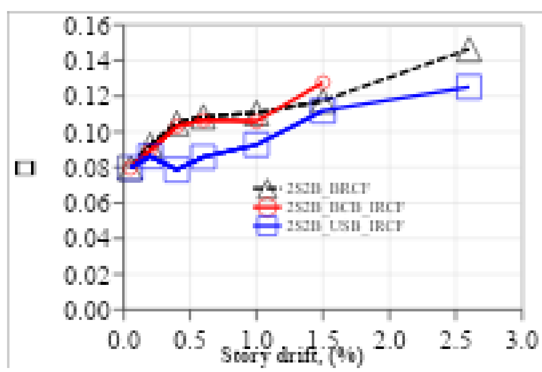


Figure 5: Equivalent viscous damping ratio of three specimens

3.3 Failure Mechanism

Typical failure modes included diagonal cracking, corner crushing, and frame–infill separation. AAC panels exhibited earlier cracking and more brittle behavior, whereas SC panels showed more distributed cracking and improved ductility. Crack initiation and propagation reflected the relative stiffness and strength of the infill-frame system. As observed from the experiments, diagonal joint cracks were observed in all specimens, while beam-infill interface cracks appeared earlier in the SC infilled frame. The burnt brick infilled specimen exhibited earlier cracking and failure compared to the bare and SC infilled frames. Failure patterns indicate that the bare frame was governed by a flexural ductile mechanism with plastic hinges at beam ends, the burnt brick infilled frame showed brittle behavior due to the formation of diagonal compression struts, leading to premature failure and the SC infilled frame exhibited a flexural-dominated ductile response with distributed cracking and higher deformation capacity, attributed to its higher compressive strength. Key differences in cracking behavior, failure mode, and drift capacity are summarized in Table 3.

Table3: Difference in first crack drift, governing failure mode, ultimate drift and failure mechanism of all test specimens

Parameters	2S2B_BRCF	2S2B_BCB_IRCF	2S2B_USB_IRCF
First crack drift	+0.2%	-0.05%	+0.2%
Governing failure mode	rmation of plastic hinge at beam ends	Combined infill cracking and exterior beam–column joint damage	Combined infill cracking and ormation of plastic hinge at the beam and column ends
Ultimate drift	+3%	+1.65%	+3%
Failure mechanism	lexural-dominating weak beam pattern	Diagonal compression	Shear sliding

4. CONCLUSIONS

Based on the experimental investigation on the three specimens the following conclusions are drawn:

- Masonry infill significantly enhances the stiffness, strength, and seismic response of RC frames compared to bare frames.
- SC infilled frames exhibited higher strength, stiffness, and energy dissipation, while AAC infilled frames showed lower stiffness but greater deformability.
- SC systems demonstrated superior ductility and higher drift capacity (about 3%), whereas AAC systems exhibited brittle behavior with lower drift capacity (about 1.65%).
- Stiffness degradation occurred in all specimens; however, SC infills showed stable hysteretic behavior, while AAC systems exhibited pinching and rapid post-peak degradation.
- SC masonry infill provides improved seismic performance and is suitable for sustainable RC construction when properly considered in design.

ACKNOWLEDGMENTS

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Two Knowledge Rivers Becoming One: Water, Memory, and Empathic Engineering

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On the mesas near Tuba City in the Navajo Nation, clay is not simply soil. It carries memory. For generations, Navajo artisans have gathered clay from the land and transformed it into vessels that hold water, food, stories, and identity. The process does not begin with equations, optimization routines, or design software. It begins with observation. The artisan studies the landscape, remembers ancestral objects, learns from elders, and reflects on the form the object should take. Materials are collected carefully and respectfully. What is not needed is returned. Stories accompany making. Songs accompany reflection. Design is not separated from life; it is woven into it. A vessel therefore becomes more than an object. It becomes relationship.

Western Scientific Knowledge (WSK) system and hence engineering rarely begins this way. Engineering often begins with data. We measure, define targets, optimize systems, and maximize efficiency. This pathway has given humanity extraordinary achievements. In the water innovation space, we recycle water in spacecraft, desalinate seawater, and engineer materials capable of molecular-scale separations. Yet, somewhere along this journey, engineering became increasingly structured and recipe-driven. The WSK system gained rigor, predictability, and analytical power, but in many ways, it also lost something equally important: heuristics, creative freedom, and the designer's intimate relationship with place.

This realization formed the foundation of my recent research, where we argued that future water innovation may depend on reconnecting these two knowledge rivers; i.e., scientific rigor and Indigenous heuristics through empathic engineering.[1] The conceptual relationship between these parallel pathways and their convergence through empathic engineering is illustrated in Figure 1. The central premise is not to replace science with Indigenous knowledge (IK), nor to romanticize one system over the other. Rather, it is to recognize that each preserves something that the other lacks. Scientific systems excel at validation, quantification, and reproducibility. Indigenous systems preserve adaptation, observation, creative exploration, and environmental intimacy.[1,2]

Indigenous knowledge systems developed under very different conditions from modern science. They evolved not inside laboratories but through centuries of observation and adaptation. Innovation emerged from uncertainty, environmental feedback, necessity, and collective memory. Design unfolded through making, where observation informed intuition, intuition guided experimentation, and experimentation drove adaptation. The process remained open and dynamic. Knowledge was not reduced to fixed rules. Instead, it evolved heuristically. This preservation of creative freedom is perhaps one of the most remarkable characteristics of Indigenous systems and one that modern engineering increasingly needs again.[3,4]

Such innovation becomes evident when we examine Indigenous innovations around the world. The *Waru Waru* systems of the Andes buffered crops against frost and drought through raised fields and surrounding canals that regulated moisture and temperature.[5] The Zuni people developed waffle gardens that retained water and created agricultural microenvironments under arid conditions.[6] Across Pacific islands, traditional catchment systems integrated water harvesting, natural filtration, and groundwater recharge directly into the landscape.[1] These were not merely technologies; they were adaptive design systems developed through observation, iteration, and long-term interaction with nature. Their laboratories were rivers and mountains. Their textbooks were stories. Their datasets extended across generations.

One of the most striking lessons from our collaboration with Navajo artisans was discovering how closely Indigenous making resembles engineering while simultaneously extending beyond it. The artisan observes previous designs, mentally envisions possibilities, experiments with materials, reflects, adjusts, and repeats. The process mirrors engineering cycles of ideation, prototyping, testing, and redesign. Yet another dimension exists. The artisan also asks whether the object belongs, whether it respects the land, what should be returned, and whether future generations inherit balance. Engineering often asks whether something can be built. Indigenous systems ask whether it should be built this way. Empathic engineering asks both.[1,7]

I often think of this relationship as two rivers. The metaphorical convergence of these rivers is illustrated in Figure 1. One river carries equations, mechanistic understanding, experimentation, and scientific rigor. The other carries memory, stories, observation, heuristics, and creative freedom. For centuries these rivers flowed in parallel. The scientific river became increasingly powerful and generated treatment plants, reactors, membranes, predictive models, and sophisticated infrastructure. Yet the same scientific river also narrowed the design space. Optimization often replaced exploration. Rules replaced intuition. Engineering became increasingly efficient but sometimes less imaginative.

The knowledge river followed another path. It preserved flexibility. It preserved adaptation. It preserved relationships with land and community. Most importantly, it preserved designer freedom. This freedom matters because the environmental challenges of the twenty-first century increasingly resemble the conditions under which Indigenous systems evolved: uncertainty, variability, disturbance, and adaptation. Climate change is altering environmental systems in ways that rigid frameworks alone may struggle to address. Thus, adaptive thinking becomes essential once more. Heuristics regain importance, and creative exploration becomes imperative. The future engineer may need to recover what Indigenous systems never lost.[3,4]

Our work argues that convergence begins not through technology but through listening. Engineers first understand place. They observe landscapes. They learn histories. They speak with communities. Design objectives emerge jointly rather than being imposed externally. Scientific principles remain essential, but they become braided with environmental memory and community understanding. In our work with Navajo collaborators, this philosophy inspired treatment concepts rooted in pottery and basket-making traditions, where local materials, traditional processing methods, and scientific principles entered the same design space. Neither system replaced the other. They converged.[1]

Perhaps children understand this idea better than adults. Ask a child to draw a river and they rarely draw only water. They draw birds, mountains, fish, trees, clouds, and people. The river belongs to a living world. Engineering education sometimes teaches the opposite by separating systems into isolated variables and components. This reductionism and tendency toward fragmentation gave science extraordinary power, but children remind us that relationships persist.

Climate change is not merely temperature increase. Water scarcity is not merely hydrology. Environmental injustice is not merely infrastructure. These are connected problems, and connected problems require connected thinking. The future engineer may therefore require new skills. The ability to calculate, model, and experiment will remain essential. But equally important may become the ability to listen, observe, imagine, and reflect. The future engineer may become part scientist, part designer, and part storyteller. The future of engineering thus may not lie in choosing between WSK and IK. It may lie in convergence. A water filter can remove contaminants and preserve identity simultaneously. A treatment system can satisfy regulations while honoring culture. Technology can be innovative and ancestral at the same time.

Water has always connected worlds. Rain connects sky with earth. Rivers connect mountains with oceans. Perhaps water can also drive the confluence of the apparently parallel knowledge rivers. And perhaps the greatest engineering innovation of the future will not be another membrane, catalyst, or reactor. Perhaps it will be learning how to design with empathy. Because water carries chemistry. But water also carries memory. Let us remember that human innovation did not begin with modern science; it has been shaped through nearly 70 millennia of observation, adaptation, creativity, and lived experience.

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Figure 1. Two rivers becoming one: a conceptual illustration of empathic engineering as a convergent pathway between Western Scientific Knowledge (WSK) and Indigenous Knowledge (IK) systems. The scientific river emphasizes rigor, experimentation, optimization, and technological innovation, whereas the knowledge river preserves observation, memory, heuristics, creative freedom, and community stewardship. Their confluence symbolizes an empathic design framework where scientific rigor and Indigenous wisdom co-evolve to produce adaptive, culturally grounded, and sustainable water innovations.

Application of Statistics in Stormwater Management Design- a Case Study of Translating Theory into Municipal Infrastructure Development

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ABSTRACT: There is no scope for denying the fact that holistic stormwater management design is very crucial for sustainable urban development. Urbanization significantly alters natural hydrologic processes by increasing impervious cover, reducing infiltration, and increasing peak runoff rates, thereby elevating flood and erosion risks (Ontario Ministry of the Environment [MOE], 2003). Modern stormwater management practice emphasizes replicating pre-development hydrologic conditions in post-development scenarios to ensure environmental protection and infrastructure resilience.

Statistical concepts are fundamental to hydrology and water resources engineering, enabling the characterization of rainfall variability, estimation of design storms, risk assessment, and infrastructure sizing (Chow, Maidment, & Mays, 1988). This paper presents a few statistical methods used in hydrologic analysis, such as frequency analysis, regression analysis, coefficient determination, etc. A subdivision stormwater management pond design is presented as a case study illustrating how these statistical tools are applied to meet municipal approval requirements for the stormwater management pond design, which ensured sustainable urban development in the study area.

Keywords: Stormwater Management, Hydrology, Statistics, Regression Analysis, Model Calibration, SWM Pond

1. INTRODUCTION

Urban development replaces natural landscapes with impervious surfaces such as houses, roads, rooftops, sidewalks, parking lots, etc. These changes disrupt the natural hydrologic cycle, leading to increased surface runoff, reduced infiltration, and higher peak flows (MOE, 2003). As a result, stormwater management has become a critical component of urban infrastructure planning.

Hydrologic variables such as rainfall and runoff are inherently stochastic. Therefore, statistical methods are essential for interpreting historical datasets, predicting future conditions, and designing infrastructure systems that are both safe and cost-effective (Viessman, Lewis, & Hammer, 2009).

Below, a few statistical concepts in hydrology are presented, and thereafter a case study is presented in which a stormwater management pond has been designed, enabling sustainable urban development in the City of Hamilton, Ontario, Canada.

2. STATISTICAL CONCEPTS IN HYDROLOGY

2.1 Frequency Analysis and Return Period

Frequency analysis is used to estimate the probability of occurrence of rainfall events. A return period (T) represents the average recurrence interval of a storm event of given magnitude (Chow et al., 1988). For example, a 100-year storm has a 1% probability of exceedance in any given year. Normally used design storms in urban stormwater management system design are 2-year, 5-year, 25-year, and 100-year events.

2.2 Regression Analysis, Coefficient of Determination (R^2), Nash–Sutcliffe Efficiency (NSE)

Regression Analysis

Regression analysis is a core statistical method used to develop empirical relationships between hydrologic variables. Hydrologic systems are influenced by multiple interacting factors including rainfall intensity, watershed area, slope, soil type, and land use. Regression techniques allow these relationships to be quantified mathematically for prediction and design purposes (Chow et al., 1988).

In stormwater engineering, regression is commonly used to estimate peak discharge, runoff volume, and runoff coefficients based on rainfall and watershed characteristics. A simple linear regression model is expressed as:

$Y = a + bX$; where Y represents the dependent variable (i.e., peak flow), X represents the independent variable (i.e. the water level).

Coefficient of Determination (R^2)

The coefficient of determination (R^2) is one of the most commonly used statistical indicators for evaluating the performance of regression models and hydrologic simulations. It measures the proportion of variance in the observed dataset that is explained by the predictive model. In hydrologic applications, (R^2) provides an indication of how well simulated values reproduce the variability observed in measured data (Moriasi et al., 2007).

Values of R^2 range from 0 to 1, where a value of 1 indicates perfect agreement between observed and predicted values, while a value close to 0 indicates little or no correlation. During hydrologic model calibration, engineers often seek to maximize (R^2) to improve confidence in model predictions and ensure that the model adequately captures watershed response characteristics.

Although high R^2 values generally indicate good model performance, researchers have noted that R^2 alone may not fully represent predictive accuracy because it primarily measures correlation rather than the magnitude of prediction errors (Legates & McCabe, 1999). Consequently, R^2 is often used in conjunction with other performance indicators such as the Nash–Sutcliffe Efficiency (NSE) to provide a more comprehensive evaluation of hydrologic model performance.

Nash–Sutcliffe Efficiency (NSE)

The Nash–Sutcliffe Efficiency (NSE), originally developed by Nash and Sutcliffe (1970), is one of the most widely accepted performance measures for hydrologic model calibration and validation. Unlike the coefficient of determination, which primarily measures correlation, NSE evaluates how closely simulated values match observed values by comparing the residual variance of the model predictions with the variance of the observed data. The NSE is expressed as:

; where Model predicted value at time t; = Observed value at time t; =Mean of the observed data over the entire evaluation period; T= Total number of time steps

In stormwater management applications, NSE is frequently used during model calibration to evaluate simulated hydrographs, runoff volumes, and peak discharge estimates. Because NSE directly accounts for prediction errors, it is often regarded as one of the most robust and informative performance indicators for assessing the reliability of hydrologic and hydraulic models used in stormwater infrastructure design.

2.3 Intensity-Duration-Frequency (IDF) Curves

IDF curves define rainfall intensity as a function of storm duration and return period. For a particular return period, the average intensity (I) of rainfall of duration T can be calculated based on the following equation:
; where a, b, and c are IDF coefficients that are unique to each municipality. IDF coefficients are developed for each municipality by analyzing long-term (i.e. 30 years) rainfall records of different durations and frequencies.

2.4 Rating Curves and Application of Regression

A rating curve defines the relationship between water level (stage) and discharge in open channels or hydraulic structures. Because continuous flow measurement is difficult, stage is measured and converted to discharge using empirical relationships derived from regression analysis (ASCE, 1996). The general form of a rating curve is:
; where Q is discharge, H is water level, H_0 is zero-flow stage, and a and b are regression coefficients.

Rating curves are widely used in: Stormwater Pond outlet calibration, River discharge estimation, Flood forecasting, Hydrologic model validation, etc. In stormwater management ponds, rating curves define outlet structure performance, ensuring that controlled release rates meet municipal criteria under varying water levels.

3. CASE STUDY: STORMWATER MANAGEMENT POND DESIGN

3.1 Project Overview

The study area is located (in the City of Hamilton) south of Rymal Road East and West of Highway 56 (HWY56); previously greenfield (undeveloped land) has been proposed to be developed as a subdivision. The subject site is about 71.33 ha. In pre-development conditions, this vast undeveloped land drains through localized channels that pass through the existing culvert under Swayze Road, connecting to the local ditches through the existing subdivision east of Swayze Road, ultimately draining to Sinkhole Creek (A tributary of Twenty Mile Creek located south of HWY56).

Obviously, the proposed subdivision development will increase the impervious cover at the subject site which will increase runoff and uncontrolled runoff from the proposed development will overburden the downstream reaches of Sinkhole Creek. Furthermore, a ‘Rapid Geomorphic Assessment’ (RGA) study identified that some reaches of Sinkhole Creek are vulnerable to erosion under existing conditions.

Therefore, as one of the requirements of the approval for the proposed subdivision development at the subject site, the local municipality (The City of Hamilton) demanded that the runoff release rate for 2 to100 year storm events from the subject development should not exceed the corresponding predevelopment level and the predevelopment level 2- to 100-year flow target at Sinkhole Creek should be determined based on existing conditions model calibration.

3.2 Methodology

In order to meet the City requirements for the stormwater management approval, the following methodology was adopted in the analysis and design:

Step 1: The existing conditions hydrologic model was created. PCSWMM model was selected for hydrologic and hydraulic modeling for this project. The subject development site is 71.33 ha; in addition to that there is an existing subdivision to the north known as Deerfield Estate (which has its own stormwater management pond providing stormwater runoff quantity and quality control), 26.49 commercial lands known as Walmart lands (which also has its own stormwater management pond providing stormwater quantity and quality control for this area) both outlets to the road side ditches along Swayze road which being conveyed through the Swayze culvert and ultimately outlets to the Sinkhole Creek through exiting culvert at HWY56. In addition, drainage analysis reveals that there is an additional 71.91 ha area that drains to the Sinkhole Creek storm outlet under existing conditions. The existing conditions model was built (PCSWMM model) and is presented in **Figure 1**. **Figure 2** shows the proposed conditions of the PCSWMM Model at the subject site.

Step 2: Rainfall data were obtained from gauging stations, and corresponding water levels were obtained from flow monitoring locations. Water level data were then converted to discharge data by using the rating curve or equation developed for the gauging stations. The flow monitoring locations or gauging stations and corresponding rating curves/equations can be found in **Figure 3.**

Figure 1: Existing Conditions PCSWMM Model of the Study Area

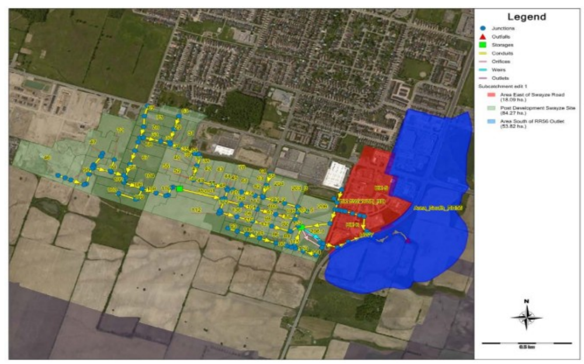


Figure 2: Proposed Conditions PCSWMM Model of the Subject Site

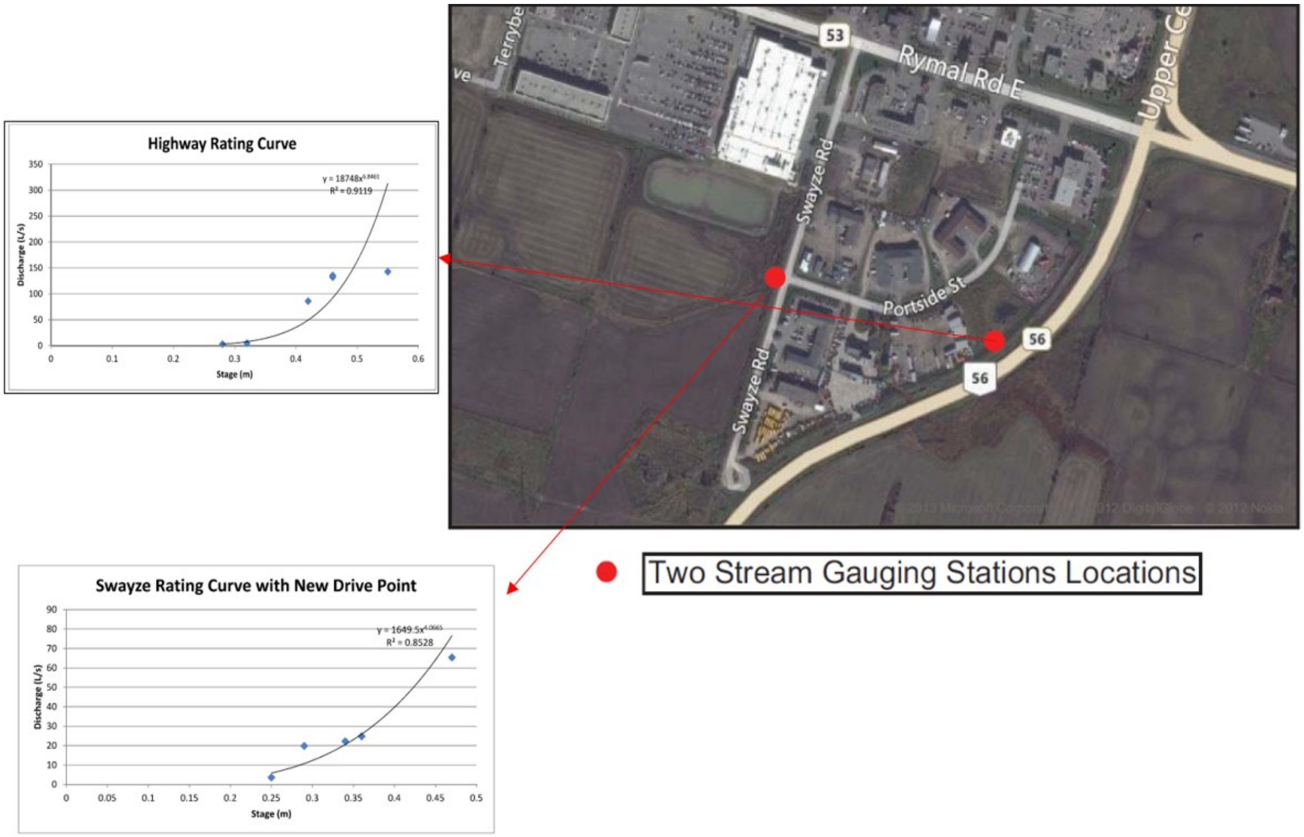


Figure 3: Flow Monitoring Location and Corresponding Rating Curve/ Equation

The observed rainfall and corresponding discharge data were available from 08 April 2013 to 26 November 2014. The data were then scanned, and outlier values were discarded from analyses. Outlier values are high discharge or water level value but corresponding low rainfall inputs and vice versa. The observed rainfall data and corresponding flow data (for the duration of 08 April 2013 to 26 November 2014) can be seen in **Figure 4** and some of the outlier values are circled on this figure as example. Rainfall events less than 2.5 mm were discarded from the analyses.

Finally, two sets of the observed rainfall and discharge data were selected: one set (from April 25 to August 21, 2013) was used for model calibration, and another set (from April 01 to August 31, 2014) has been used in model validation. The duration for calibration and validation (from April to August of two different years) selected such that hydrologic response in terms of flow is high due to spring melt and rainfall inputs at this time of the year in Hamilton region. The understanding was that studying the hydrologic response during high flow season would provide good confidence in the model calibration results.

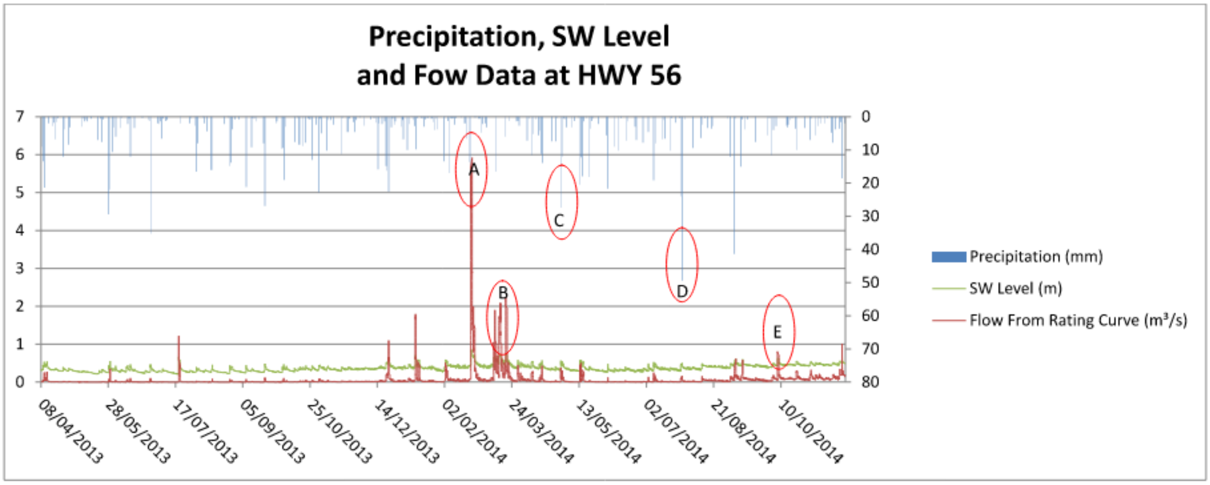


Figure 4: Observed Rainfall, Corresponding Water Level and Flow Data

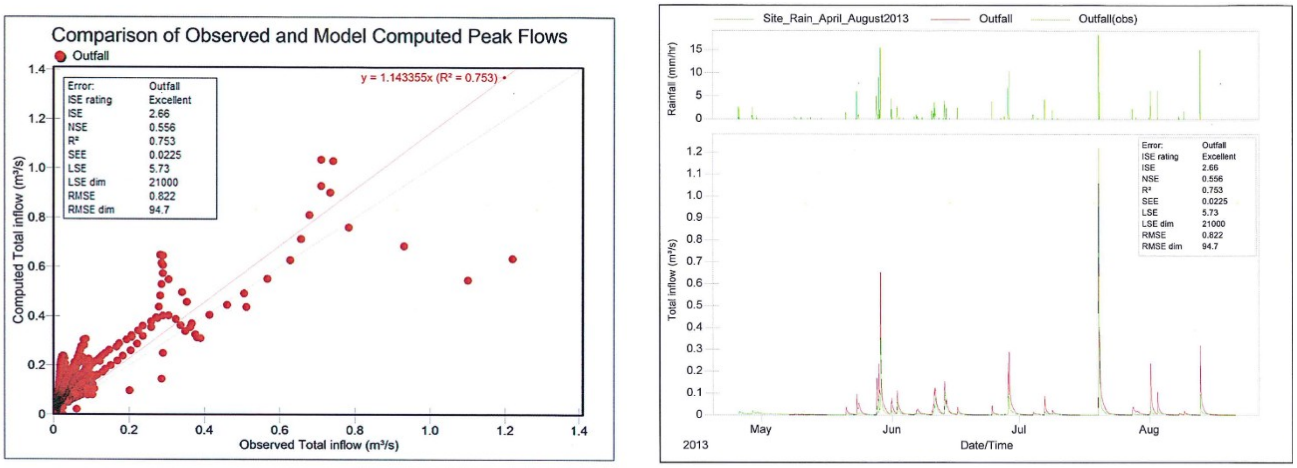
Step 3: Based on the observed flow data (obtained in step 2 above), the existing conditions model was calibrated based on the *statistical analysis*. With the selected observed rainfall and discharge data the model hydrological parameters such as sub-catchment width, CN values, depression storage, etc. were adjusted (i.e. Calibrated) such that there is acceptable model flow prediction based on the observed discharge value. The statistical parameters R^2 >0.5 and NSE>0 was considered to be the minimum acceptable limit of the correlation between the model computed and observed values.

Step 4: Sensitivity analysis was performed with 2 to 100 year design storm events of various durations (3 hour, 6 hour,12 hourr, 24 hour) and type (SCS, Chicago). Based on the sensitivity analysis results, Chicago 24 hour rainfall (2 year to 100 year return period) was selected as the design rainfall. The 24 hour design rainfall depth for different frequency or return periods (2 to 100 year) was determined based on City of Hamilton's IDF curves.

Step 5: The existing condition hydrologic was run with design storm events with 2 year, 5 year, 10 year, 25 year, 50 year and 100 year return periods to set the predevelopment target release rate which should be maintained in the post development conditions for the respective storm events. Then the target predevelopment flow for 2 to 100 year storm events were found my running the existing conditions calibrated model with corresponding design storm events (Chicago 24 hour).

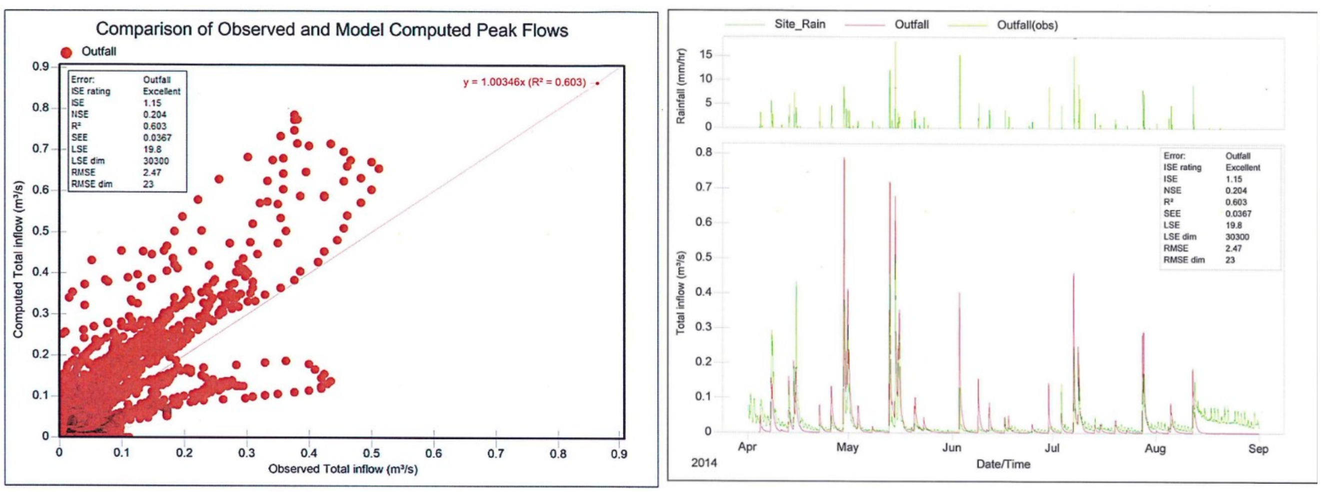
Step 6: In the next step, post development hydrologic and hydraulic model (using proposed subdivision land use such as roads, houses, stormwater management pond etc.) was created in PCSWMM model. The subdivision development proposed two stormwater management pond. One dry pond for providing stormwater quantity control for upstream lands and one wet pond providing further stormwater quantity control as well as quality control for all upstream lands including the subject site (71.33 ha), Deerfield and Walmart site. The post development was created in PCSWM model with the aid of GIS software such as AutoCAD Civil 3D and free domain GIS platform such as SAGA GIS to transform the CAD data into Esri Shape file format for import in the model. The post development PCSWMM model can be seen in **Figure 2**. The released flow from Deerfield and Walmart site has been added as an inflow to the hydraulic node, for this reason, the sub-catchment representation of these two sites are not shown on the post development PCSWMM model.

Step 7: With calibrated model parameters (obtained in *Step 3* above), the post development model was then run with the design rainfall with various return period (i.e. 2 year, 5 year, 10 year, 50 year and 100 year) and SWM pond was designed (i.e. flow control orifice and weir were sized) so that the released discharge at the Sinkhole Creek Outlet does not exceed the predevelopment flow target obtained *Step 4*). Regression-based rating curves were used to define outlet discharge characteristics of the stormwater management pond.



(a) (b)

Figure 5: a) Calibration Model Run from April 25 to August 21, 2013. (R^2 = 0.753 and Slope of the Line of Regression = 1.14); b) shows observed and model-computed hydrograph during calibration model run



(a) (b)

Figure 6: a) Validation Model Run from April 01 to August 31, 2014; (R^2 = 0.603 and Slope of the Line of Regression = 1.00); b) shows observed and model computed hydrograph for the validation model run

4. RESULTS AND DISCUSSIONS

Figure 5 shows the R^2 =0.7 and NSE= 0.556 for the calibration model run in PCSWMM with observed rainfall and discharge data (from April 25 to Augst 21, 2013). The slope of the Regression line between model predicted and observed flow is 1.14 (close to 1), which suggests good correlation between the model predicted and observed values.

With the same calibrated parameters, the existing conditions PCSWMM model was re-run with the second set of observed rainfall and flow data (for the period of April 01 to August 31, 2014) for model validation (i.e. to further validate the performance of model prediction). **Figure 6** shows R^2 =0.603 and NSE= 0.204 for the validation model run (from April 01 to Augst 31, 2014). The slope of the regression line is also almost 1 which indicates very good correlation between the observed and predicted flow and very good confidence in the model predictability (i.e. model calibration).

Based on the above, the statistical parameter values helped to decide on the confidence level of the model calibration, and based on the calibrated model, the SWM pond was designed and further refined based on the advice from the municipality and a peer review consultant before obtaining final approval from the approval authorities – City of Hamilton.

5. CONCLUSIONS

Statistical concepts are essential in hydrology and stormwater management design. Methods such as frequency analysis, regression modeling, and rating curve development provide the foundation for modern engineering practice. The case study demonstrates that integrating statistical tools into stormwater pond design enables effective flood control, regulatory compliance, and sustainable urban development.

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PART II

Automation and Emerging Technologies

Papers 006–009

Advancing Engineering for a Sustainable Future (AE4SF) - 1st Int Symposium

Harrison Hot Springs, British Columbia, Canada
July 4, 2026

Healthcare Innovation: Emerging Opportunities for Engineering Solutions

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ABSTRACT: Healthcare systems worldwide face escalating costs, workforce shortages, aging populations, and increasing demand for services, creating significant sustainability challenges. This paper examines emerging healthcare innovations that can improve system performance while controlling expenditure growth. Key trends include artificial intelligence, digital health, precision medicine, robotics, intelligent healthcare infrastructure, digital twins, perioperative system transformation, and sustainable healthcare practices. These innovations are increasingly converging into interconnected Healthcare 4.0 ecosystems that integrate patients, providers, infrastructure, devices, and data to support predictive, personalized, and efficient care delivery. The paper highlights the critical role of engineering disciplines in enabling these advancements through systems integration, automation, analytics, infrastructure design, and medical technology development. As an example of engineering-led healthcare innovation, the paper presents ongoing research at the University of Alberta focused on reducing work-related musculoskeletal disorders among cardiac sonographers using wearable sensors, artificial intelligence, computer vision, and digital-twin technologies. Future healthcare will rely on interconnected, technology-enabled systems and multidisciplinary collaboration to deliver resilient and sustainable care.

1. INTRODUCTION

Healthcare systems around the world are experiencing sustained expenditure growth, raising concerns about long-term affordability and system sustainability. According to 2025 reports by the Canadian Institute of Health Information (CIHI), total health spending in 2025 was projected to reach $399 billion, accounting for 12.7% of GDP(CIHI, 2025a; CIHI, 2025b). Moreover, health spending in Canada grew by 7.4% in 2023 and 6.1% in 2024, which outpace broader economic expansion, indicating that health care is consuming an increasing share of national resources (CIHI, 2025a). Figure 1 presents the provincial health expense per capita for selected Canadian provinces, which shows steady upward trend over the last 20 years. On the other hand, healthcare expenses per capita in the United States is the highest among comparable OECD countries (Telesford et al., 2026). However, despite this high level of investment, improvements in health outcomes and access have not consistently matched spending increases, highlighting inefficiencies in the system (Kuehn, 2021).

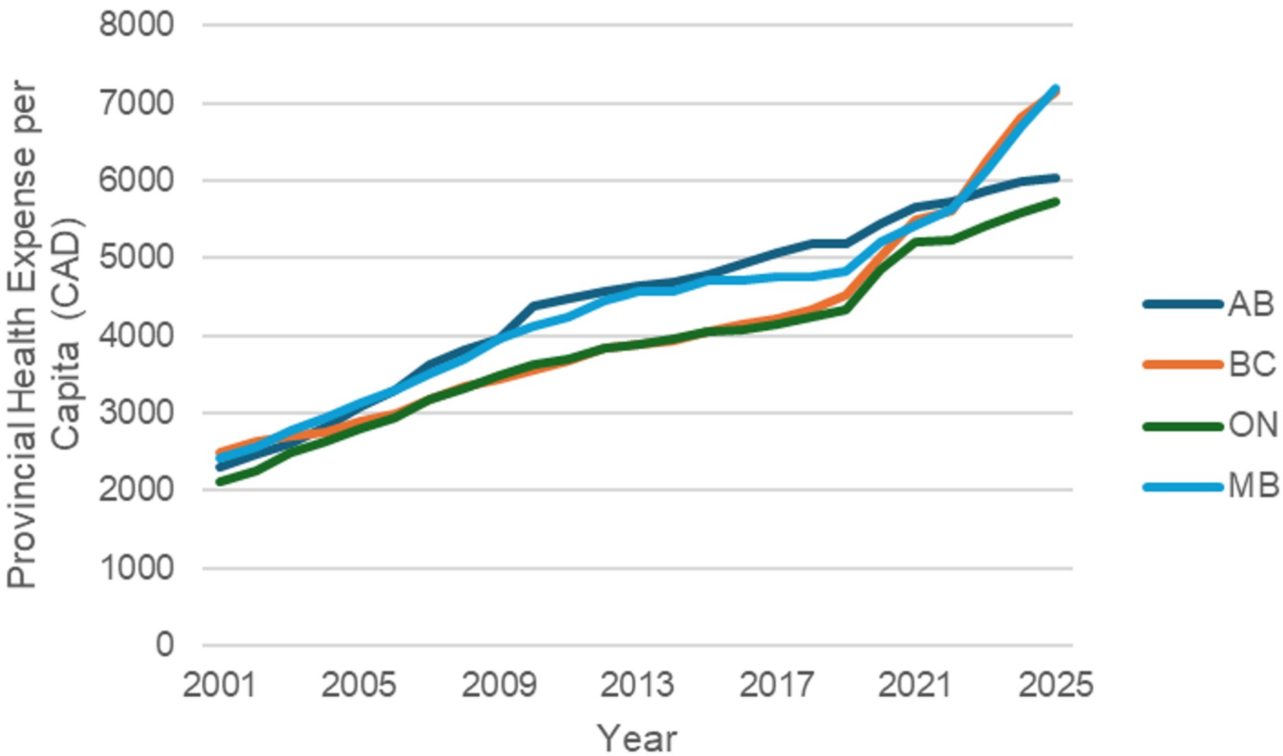

Figure 1: Provincial Health Spending per Capita (CAD) for Selected Provinces
(Data Source: CIHI, Statistics Canada)

These trends underscore sustained medical inflation, which is defined as the rate at which healthcare costs increase over time. In Canada, expenditure growth is primarily driven by population growth, aging, and general inflation, along with increasing service utilization (CIHI, 2025a). Rapid population growth in recent years has further strained the system, limiting real per capita spending gains despite nominal increases (CIHI, 2025b). In contrast, the U.S. experience illustrates a different dimension of medical inflation: price escalation. Evidence shows that higher spending in the United States is largely attributable to higher prices for services, pharmaceuticals, provider wages, and administrative costs rather than increased utilization (John Hopkins Bloomberg School, 2019).

The persistence of medical inflation presents a fundamental sustainability challenge. When health expenditures grow faster than GDP, governments face increasing fiscal pressure, and health systems risk diverting resources from other public priorities. Moreover, simply increasing funding does not guarantee improved system performance, as evidenced by international comparisons where high-spending systems do not consistently achieve better outcomes (Kuehn, 2021).

Innovation in health care is therefore critical to bending the cost curve while maintaining or improving the quality of care. Key areas of opportunity include the digitization of care delivery, the transition from hospital-centric models to community-based and preventive care, and the deployment of advanced medical technologies. Recent advancements in areas such as artificial intelligence, robotics, and telehealth platforms have the potential to optimize clinical workflows, reduce administrative burdens, and improve access to care—particularly in high-cost systems where inefficiencies are prevalent (Anderson et al., 2019). At the same time, shifting care to lower-cost settings and emphasizing prevention can mitigate demand pressures associated with aging populations and chronic disease (CIHI, 2025a).

Within this innovation landscape, engineering disciplines can play a pivotal role in shaping sustainable health care systems by contributing to the design and optimization of health infrastructure and enabling more efficient use of capital and operational resources. Opportunities are also emerging for multi-disciplinary collaborations to drive advancements in medical technologies, including minimally invasive procedures and remote monitoring devices, which reduce reliance on resource-intensive acute care environments. This paper presents some emerging opportunities where engineering solutions can be leveraged to address healthcare challenges and to advance innovation, and also some related research initiatives at the University of Alberta.

2. Recent Healthcare Innovation Around the World

Healthcare systems worldwide are facing growing pressures from aging populations, increasing prevalence of chronic disease, workforce shortages, rising patient expectations, and sustained expenditure growth (WHO, 2021; OECD, 2023; CIHI, 2025a). At the same time, advances in artificial intelligence (AI), robotics, digital health, advanced diagnostics, data analytics, automation, and connected devices are creating unprecedented opportunities to improve healthcare delivery, operational efficiency, and system sustainability (Topol, 2019; Hashimoto et al., 2018; Ahsan & Siddique, 2022). Increasingly, healthcare innovation is evolving beyond individual technologies toward integrated systems that connect patients, providers, infrastructure, devices, and data through digitally enabled ecosystems.

This transformation reflects the emergence of Healthcare 4.0, a paradigm adapted from Industry 4.0 principles that incorporates cyber-physical systems, Internet of Medical Things (IoMT) technologies, cloud computing, AI, digital twins, advanced analytics, and automation to create intelligent, interconnected healthcare environments (Ahsan & Siddique, 2022; WHO, 2021). These technologies are enabling healthcare organizations to move from reactive models of care toward predictive, personalized, and data-driven systems capable of supporting continuous improvement across clinical, operational, and infrastructure domains.

For engineers, this transition creates significant opportunities beyond traditional healthcare infrastructure projects. Engineering expertise is increasingly required to support intelligent facility design, digital infrastructure, systems integration, advanced sensing technologies, predictive modelling, automation, cybersecurity, sustainability, and medical device innovation. The following sections highlight key global innovation trends and emerging opportunities that are reshaping healthcare delivery.

2.1 Artificial Intelligence and Data-Driven Healthcare

Artificial intelligence has emerged as one of the most transformative healthcare innovations of the past decade. Advances in machine learning, computer vision, natural language processing, and generative AI are enabling healthcare organizations to derive meaningful insights from increasingly large and complex datasets (Jiang et al., 2017; Topol, 2019). AI applications are now reported across radiology, pathology, cardiology, oncology, genomics, and surgery, where algorithms support disease detection, image interpretation, risk prediction, and clinical decision-making (Topol, 2019; Hashimoto et al., 2018).

Current applications include:

- Clinical decision support systems
- Automated medical image interpretation
- Predictive analytics and risk stratification
- Natural language processing and clinical documentation
- Operational forecasting and resource optimization
- Generative AI-assisted knowledge management

Machine learning models have demonstrated potential to identify patients at risk of deterioration, hospital readmission, adverse events, and postoperative complications, enabling earlier intervention and more efficient allocation of healthcare resources (Jiang et al., 2017; Topol, 2019). Beyond clinical applications, AI is increasingly being used to optimize scheduling, staffing, patient flow, capacity planning, and supply chain operations (OECD, 2023).

Recent advances in foundation models and generative AI have further accelerated interest in healthcare applications. Emerging systems can summarize clinical documentation, assist with information retrieval, support administrative workflows, and facilitate communication among healthcare teams. While these technologies offer considerable promise, challenges related to data quality, bias, transparency, governance, privacy, and regulatory oversight remain important considerations for implementation (Topol, 2019; WHO, 2021).

2.2 Digital Health, Virtual Care, and Connected Systems

Digital health technologies have expanded rapidly worldwide, particularly following the COVID-19 pandemic, which accelerated adoption of virtual care and remote monitoring models (Keesara et al., 2020; WHO, 2021). Digital health encompasses a broad range of technologies that facilitate healthcare delivery, communication, monitoring, and decision-making beyond traditional clinical settings.

Current innovations include:

- Virtual care and telehealth platforms
- Remote patient monitoring systems
- Wearable and implantable sensors
- Mobile health applications
- Hospital-at-home programs
- Internet of Medical Things (IoMT) ecosystems

These technologies enable healthcare services to extend beyond hospitals and clinics, supporting more patient-centered models of care. Remote monitoring platforms can continuously collect physiologic information from patients in community settings, facilitating earlier detection of deterioration and reducing unnecessary hospital utilization (WHO, 2021). Virtual care programs have demonstrated benefits in improving access, particularly for rural and remote populations, while supporting chronic disease management and specialist consultation services (OECD, 2023).

The expansion of connected healthcare systems presents substantial engineering opportunities related to telecommunications, interoperability, cloud computing, cybersecurity, and digital infrastructure design. As the number of connected medical devices continues to increase, healthcare organizations must ensure reliable communication, secure data exchange, and resilience across increasingly complex digital ecosystems (WHO, 2021).

2.3 Precision Medicine and Advanced Diagnostics

Advances in genomics, molecular biology, computational science, and biomedical engineering are driving the transition toward precision medicine, which seeks to tailor prevention, diagnosis, and treatment strategies to individual patient characteristics (Collins & Varmus, 2015; Ashley, 2016). Rapid reductions in the cost of genomic sequencing, combined with advances in bioinformatics and computational analytics, have expanded the clinical applicability of personalized medicine across oncology, cardiology, rare diseases, and pharmacogenomics (Ashley, 2016). Simultaneously, advances in molecular diagnostics, biomarker detection, and liquid biopsy technologies are enabling earlier and more precise disease detection.

Key innovations include:

- Genomic and molecular diagnostics
- Precision oncology and targeted therapies
- Liquid biopsy technologies
- AI-assisted diagnostic platforms
- Point-of-care testing systems
- Advanced biomarker detection technologies

Beyond genomics, innovations in imaging, biosensing, and portable diagnostic technologies are bringing advanced diagnostic capabilities closer to the patient. Handheld ultrasound devices, wearable sensors, and point-of-care testing platforms are enabling rapid diagnosis in both hospital and community settings (WHO, 2021).

Engineering contributions are central to these developments and include laboratory automation, sensor development, computational biology, software engineering, advanced instrumentation design, and large-scale data management. Future advances will increasingly depend on the integration of biological, clinical, and operational data to support personalized care pathways.

2.4 Intelligent Healthcare Infrastructure and Digital Twins

Healthcare facilities are becoming increasingly sophisticated environments where physical infrastructure, digital technologies, medical devices, and operational systems must function as integrated ecosystems. This evolution has led to growing interest in digital twins, simulation modelling, and intelligent infrastructure platforms capable of supporting real-time monitoring and operational optimization (Pellegrino et al., 2025; Shen et al., 2024).

Key innovations include:

- Digital twin platforms
- Smart hospitals and intelligent buildings
- Real-time asset monitoring systems
- Predictive maintenance technologies
- Advanced building automation systems
- Integrated facility management platforms

Digital twins are virtual representations of physical systems that continuously update using real-world data. In healthcare, digital twins are being explored to model patient pathways, clinical operations, infrastructure utilization, workforce planning, and facility performance (Pellegrino et al., 2025). Recent reviews suggest significant potential for digital twins to support precision medicine, operational optimization, and predictive decision-making, although challenges related to interoperability, validation, and governance remain substantial (Shen et al., 2024). These developments align closely with engineering disciplines focused on systems integration, simulation modelling, operations research, and infrastructure resilience.

2.5 Horizon Scan: Perioperative System Transformation and Surgical Innovation

Surgical care represents one of the most technologically advanced and operationally complex domains within healthcare. Historically, innovation focused primarily on individual procedures or devices. Increasingly, however, surgical services are being conceptualized as integrated perioperative systems that connect patients, clinicians, devices, infrastructure, sterile processing, supply chains, analytics platforms, and operational workflows (ORNAC, 2025; Accreditation Canada, 2019).

Growing procedural demand, workforce shortages, fiscal constraints, and sustainability concerns are driving efforts to improve efficiency, safety, and access through system-level innovation (CIHI, 2025a; CIHI, 2025b). Professional and regulatory standards increasingly emphasize coordinated perioperative care, infection prevention, workflow optimization, quality monitoring, and continuous improvement across the entire surgical pathway (AORN, 2025a; AORN, 2025b; ORNAC, 2025; CSA, 2016).

2.6 Minimally Invasive and Image-Guided Surgery

Minimally invasive surgery has transformed clinical practice by reducing tissue trauma, shortening recovery times, and improving patient outcomes compared with conventional open procedures (Ljungqvist et al., 2017; Kehlet, 2018). Advances in instrumentation, imaging, navigation systems, and enhanced recovery protocols have enabled increasingly complex procedures to be performed using less invasive approaches.

Key innovations include:

- Laparoscopic surgery
- Advanced endoscopic procedures
- Natural orifice surgery (NOTES)
- Percutaneous image-guided interventions
- Enhanced Recovery After Surgery (ERAS) programs

Systematic reviews consistently demonstrate reductions in length of stay, postoperative complications, pain, and opioid utilization associated with minimally invasive techniques and ERAS pathways (Ljungqvist et al., 2017; Mahmudov et al., 2025; Smith et al., 2020).

2.7 Robotic Surgery and Telerobotics

Robotic-assisted surgery has evolved into a platform technology that combines advanced visualization, precision instrumentation, digital navigation, and increasingly AI-supported guidance systems (Hashimoto et al., 2018; Lanfranco et al., 2004).

Key innovations include:

- Robotic-assisted surgical systems
- Digital navigation technologies
- Augmented and mixed reality visualization
- Image-guided robotic surgery
- Telerobotic surgical platforms

Recent advances in telecommunications infrastructure have enabled increasing interest in remote and telerobotic surgery. Systematic reviews demonstrate technical feasibility and potential to improve access to specialized care in geographically dispersed regions, although challenges related to latency, cybersecurity, regulation, and infrastructure requirements remain significant (Ding et al., 2025; Yang et al., 2026).

2.8 Integrated Operating Rooms and Procedural Environments

Operating rooms are increasingly evolving into digitally integrated procedural environments that combine imaging, communications, information systems, and clinical technologies within a unified workspace (Steris, 2018; Springer Review, 2021).

Key innovations include:

- Hybrid operating rooms
- Integrated digital operating rooms
- Real-time imaging systems
- Centralized device management platforms
- Multidisciplinary procedural suites

These environments support image-guided interventions, improve workflow continuity, reduce patient transfers, and facilitate multidisciplinary collaboration. However, they also introduce significant infrastructure requirements related to power distribution, ventilation, networking, interoperability, and lifecycle management.

2.9 Digital Supply Chains and Sterile Processing

Perioperative supply chains and sterile processing departments are increasingly being transformed through automation, analytics, and digital traceability technologies (AORN, 2025a; CSA, 2016).

Key innovations include:

- RFID-enabled inventory tracking
- Instrument lifecycle management systems

- Automated sterilization monitoring
- Predictive inventory management
- Real-time asset tracking platforms

Studies have demonstrated substantial inefficiencies in surgical inventory systems, with many instruments rarely utilized despite requiring repeated reprocessing and storage (Eussen et al., 2025; Onuh et al., 2024). Integration of inventory, scheduling, and analytics systems presents opportunities to improve efficiency, reduce waste, and enhance surgical readiness.

2.10 Perioperative Analytics and Operational Orchestration

Operating rooms are among the most resource-intensive environments within healthcare systems. Advances in analytics, simulation modelling, and digital twin technologies are enabling increasingly sophisticated approaches to operational management.

Key innovations include:

- Real-time operational dashboards
- Predictive scheduling systems
- Capacity management platforms
- Workforce optimization tools
- Digital twin simulation environments

These technologies support improved utilization, reduced delays, enhanced throughput, and more effective allocation of resources. For engineers, perioperative operations represent a growing opportunity for the application of systems engineering, operations research, machine learning, and simulation methodologies.

2.11 Sustainability and Circular Healthcare Systems

Sustainability is emerging as a major priority across healthcare systems globally. Healthcare is estimated to contribute approximately 4–5% of global greenhouse gas emissions while consuming significant energy, materials, and natural resources (MacNeill et al., 2017; Health Care Without Harm, 2023). Operating rooms are among the most resource-intensive environments within hospitals and generate substantial waste through energy consumption, disposable supplies, and complex supply chains (MacNeill et al., 2017; Savio et al., 2026).

Key innovations include:

- Energy-efficient healthcare facility design
- Sustainable procurement programs
- Device reprocessing and reuse initiatives
- Circular supply chain models
- Lifecycle-based infrastructure planning

Increasingly, healthcare organizations are adopting decarbonization strategies, waste reduction initiatives, and circular economy principles that align environmental stewardship with operational efficiency (Health Care Without Harm, 2023; NHS England, 2022). Future engineering efforts will play a critical role in developing standardized methodologies for lifecycle assessment, environmental measurement, sustainable infrastructure design, and resource optimization.

3. Occupational Ergonomic Research at the University of Alberta

This section presents an example of healthcare related research ongoing at the Occupational Ergonomic Research Lab in the Mechanical Engineering Department at the University of Alberta.

Work-related musculoskeletal disorders (WMSDs) are highly prevalent in sonography, a predominantly women profession, due to prolonged ultrasound probe handling, repetitive movements, sustained awkward postures, and the gripping and pushing forces required during scanning (Coffin, 2014). At the Mazankowski Heart Institute (Edmonton, Alberta), 292 workdays were lost over the last three years because of these types of injuries. In a 2022 national survey of Sonography Canada members (Clarke, 2022), 83% reported work-related muscle and joint problems, and 69% said they scan while in pain; their top concerns were injuries, rising productivity demands, and burnout. These injuries also affect patient care by contributing to pain, fatigue, sick leave, staffing shortages, delayed appointments, and reduced service capacity.

Echocardiography is especially important because timely, high-quality cardiac imaging supports diagnosis and ongoing management for many patients across the lifespan. However, most previous research on sonographer injury has relied on self-report surveys and interviews (Fukumura, 2024; Evans, 2009; Russo, 2002). Although informative, these approaches do not provide objective, continuous measures of physical and cognitive workload during real clinical care. Existing studies have also not established an automated, objective method for posture-based ergonomic assessment in echocardiography practice (Moon, 2019).

The primary research question is: Can automated quantification of the physical and cognitive workload experienced by sonographers help reduce work-related injuries and symptoms while maintaining clinically feasible image acquisition?

And, the central hypothesis is that AI- and computer vision-based automated quantification of the physical and cognitive demands of sonography, particularly echocardiography, can help reduce WMSDs and inform the design of ergonomic interventions. Because this research focuses on injury prevention and safer work design in a women-dominated profession, it is directly relevant to improving women's health outcomes. It is also expected to improve care delivery by supporting workforce sustainability and throughput capacity.

The objectives are to:

1. Build a multimodal dataset of cardiac sonographer workload collected from real echocardiography examinations;
2. Quantify physical and cognitive workload using objective measures;
3. Develop models to estimate probe grip and push forces from muscle signals;
4. Develop an automated approach for posture-based ergonomic assessment; and
5. Build a digital-twin model of the echocardiography work environment to test safer workflows, room layouts, and staffing scenarios.

3.1 Methodology

This is a mixed-methods, real-world study conducted in the echocardiography laboratories of the Mazankowski Alberta Heart Institute, where experienced sonographers and trainees will perform echocardiography, targeting more than 50 patient examinations, including pregnant women.

During clinical exams, sonographers will wear non-invasive sensors to measure upper-extremity muscle activity, body motion, hand grip and push forces, visual and cognitive workload indicators, and physiological demand. Synchronized videos will support computer-vision-based posture assessment. We will also collect standardized and customized questionnaires, including demographics and work factors, the Nordic Musculoskeletal Questionnaire, and NASA-TLX.

3.2 Expected Outcomes and Significance

This project is expected to generate five main outcomes:

1. The first curated multimodal dataset of sonographer workload in echocardiography;
2. Automated ergonomic assessment tools using wearable sensors aided with AI and computer vision;
3. Validated methods to estimate probe forces from muscle signals; and
4. A digital-twin model capable of testing safer room layouts, task flows, and implementation scenarios before operational changes are made.

The significance of this work is both scientific and practical. Scientifically, it will advance methods in biomechanics, ergonomics, and sensing. Clinically, it will generate evidence to guide safer design and implementation of equipment, room layout, and workflow planning. Most importantly, it directly addresses women's health by targeting injury prevention, pain reduction, and safer working conditions in a predominantly women healthcare workforce. By improving sonographers' well-being and retention, this research also has the potential to strengthen service capacity and support more timely echocardiography access for patients and families.

4. CONCLUSIONS

Healthcare innovation is increasingly characterized by convergence among artificial intelligence, advanced diagnostics, robotics, digital health, automation, sustainability, and systems engineering (WHO, 2021; OECD, 2023). Future healthcare environments are expected to function as interconnected cyber-physical ecosystems where patients, clinicians, devices, infrastructure, and digital platforms continuously exchange information to support adaptive and data-driven care delivery (Ahsan & Siddique, 2022).

Achieving these benefits will require collaboration among clinicians, engineers, computer scientists, architects, policymakers, health system leaders, and industry partners. As healthcare systems continue to evolve, engineering disciplines will play a central role in developing resilient, sustainable, and technology-enabled models of care capable of improving outcomes while addressing future healthcare challenges.

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Advancing Engineering for a Sustainable Future (AE4SF) - 1st Int Symposium

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A Comparative Review of Computer Vision Architectures for Automated Bridge Component Inspection

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ABSTRACT: In-person inspections of bridges can often be unsafe, slow, and subjective. Civil engineers are using automated computer vision frameworks to increase objectivity and scalability. This review paper presents a comparative analysis of deep learning algorithms for identifying bridge components and structural defects. We assess this technology in three areas: (1) pixel-level segmentation frameworks for high-precision defect measurement; (2) object detection architectures optimized for rapid asset localization and edge processing; and (3) emerging Vision-Language Models (VLMs) that allow text-prompted diagnostics and automated report generation. We also examine the data scarcity, showing how the lack of standardized public bridge datasets limits model performance under challenging field conditions. Finally, we discuss the integration of edge-AI drone platforms into Department of Transportation operations to support a proactive, data-driven maintenance paradigm.

1. INTRODUCTION

1.1 Structural Maintenance Challenges and the Constraints of Manual Inspection

The safety of transportation networks depends heavily on the structural integrity of bridge infrastructure. Currently, routine condition assessment relies on manual visual inspections by certified engineers. While this hands-on approach remains the standard regulatory practice, it introduces major operational limitations. The reliability of asset databases is affected by the subjective nature of manual visual evaluation, which can lead to inconsistent defect ratings among inspectors (Agdas et al., 2016). Additionally, these physical inspections are time-consuming and labour-intensive, and they can expose workers to safety risks when they access difficult locations, such as under-deck bearing assemblies or high-altitude pier caps.

In post-disaster settings, including urgent post-earthquake structural evaluations, these systemic limitations become important. Emergency response and recovery activities can be delayed by the sudden need for rapid safety clearances across a regional transportation network, revealing the practical consequences of inspection bottlenecks (Chen and Omenzetter, 2013).

1.2 Evolution of Structural Health Monitoring Frameworks

Early engineering research concentrated on contact-based Structural Health Monitoring (SHM) frameworks to lessen human subjectivity. These conventional approaches rely on dense networks of physical sensors, such as accelerometers, fiber-optic strain gauges, and acoustic sensors that are either directly incorporated in or linked to crucial bridge components (Hassan et al., 2023). Physical sensor arrays provide extremely precise, real-time data, but their permanent field deployment is constrained by high installation costs, ongoing power requirements, complicated data filtering, and weather-related damage.

As a result, civil engineering has increasingly moved toward remote, non-contact sensing techniques (Spencer et al., 2019). Inspection teams can now quickly record the visual condition of inaccessible bridge elements without building temporary scaffolding or stopping traffic, owing to the development of commercial Unmanned Aerial Vehicles (UAVs) and high-resolution digital cameras (Hoskere et al., 2019). The combination of drone technology and large-scale image collection has produced a surge of visual data, creating a need for automated systems that can convert raw imagery into useful engineering information without extensive manual filtering.

1.3 Foundations of Automated Computer Vision (CV) in Civil Engineering

Modern structural inspection workflows incorporate automated Computer Vision (CV) frameworks to efficiently process large drone datasets. CV is a specialized area of artificial intelligence (AI) that enables computers to analyze digital images. Rather than depending only on human screening, CV algorithms examine image characteristics, such as pixel colors, edge boundaries, and textures, to automatically detect structural anomalies.

Contemporary vision-based monitoring often uses Deep Learning (DL), particularly Deep Convolutional Neural Networks (DCNNs) (Hoskere et al., 2018). After training on annotated images of healthy and damaged steel or concrete components, these models can learn to identify complex structural defects (Spencer et al., 2019). These frameworks operate at three different levels of detail, depending on the underlying network architecture:

Object Detection: By creating distinct bounding boxes around the targets, object detection locates macroscopic distress zones or structural assets (bearings or pillars) (Zhou et al., 2026).

Semantic and Instance Segmentation: These methods carry out pixel-by-pixel categorization, defining the limits of spalling zones, corrosion patches, and cracks (Kalfarisi et al., 2020). This enables engineers to compute physical defect dimensions, such as surface area and crack width, directly (Parnia Shokri et al., 2022).

Multi-Modal Vision-Language Processing: These methods convert raw pixels into automated condition reports or written technical descriptions by pairing visual image encoders with large language model (LLM) decoders (Liang et al., 2025; Chen et al., 2026).

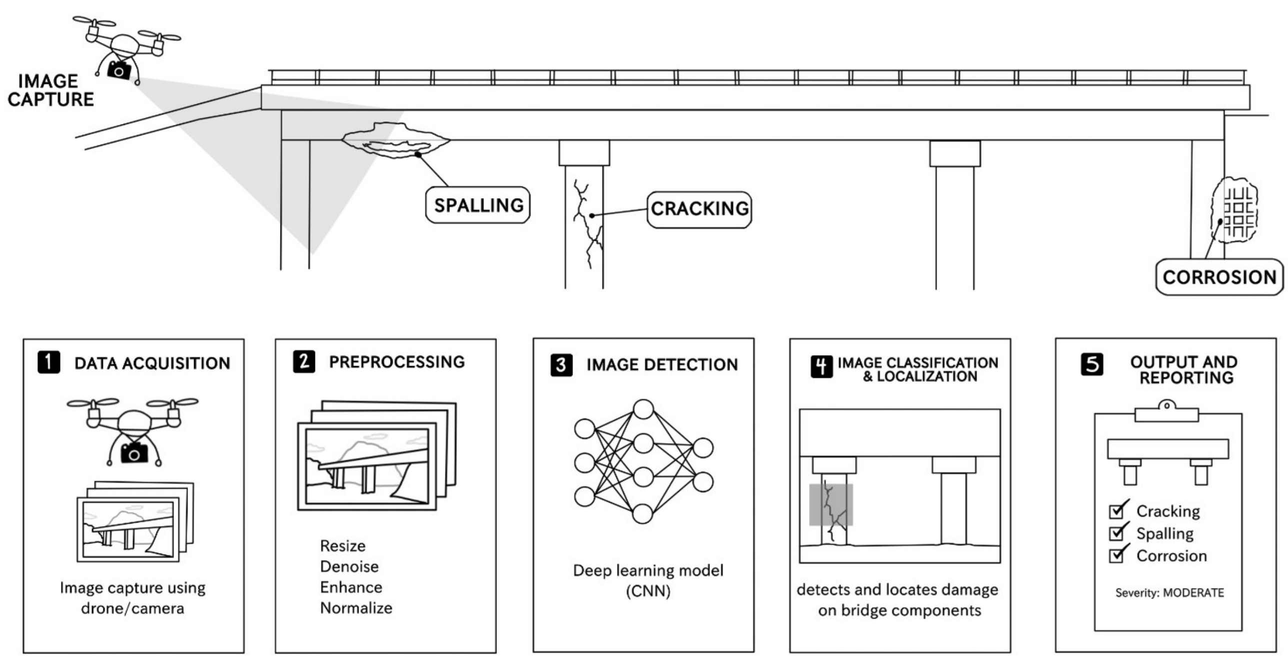

Figure.1: Automated Computer Vision (CV) Framework for Bridge Component Damage Identification.

Figure 1 illustrates a computer vision–based workflow for automated bridge inspection. Images of bridge components are collected using drones or cameras, preprocessed, and analyzed using deep learning models to detect, classify, and localize damage. Typical damage types include cracking, spalling, corrosion, and bearing deterioration in bridge decks, girders, piers, and other structural elements. The system generates inspection reports to support rapid condition assessment, maintenance planning, and asset management.

1.4 Objective and Scope of this Review

A systematic assessment of vision-based frameworks is crucial as artificial intelligence becomes increasingly integrated into civil engineering. The main goal of this paper is to present a concise, comparative analysis of computer vision architectures for automated identification of bridge components and associated damage.

2. OBJECT DETECTION AND BOUNDING-BOX ARCHITECTURES

2.1 Methodology and Application

By estimating spatial coordinates and creating bounding boxes around targets, object detection architectures locate structural assets or macro-level flaws (Hoskere et al., 2018). In bridge engineering, this is used for automated asset mapping (cataloging piers, girders, and bearings) and rapid anomaly detection (spotting severe spalling or corrosion). Inspection teams can quickly scan thousands of drone photos and identify high-priority flaws for human review because of these models' convolutional backbone feature extraction (Spencer et al., 2019).

2.2 Two-Stage vs. Single-Stage Models

The goal of developing structural object detection is to strike a balance between localized accuracy and computational speed:

Two-Stage Detectors (such as Faster R-CNN): These networks first generate candidate regions and then classify them. Their multi-step pipeline can be computationally slow, despite its accuracy in recognizing complex bridge components (Hoskere et al., 2018).

Single-Stage Detectors (e.g., YOLO, SSD): Modern frameworks often prioritize single-stage models that predict bounding boxes and defect classes in a single pass. This significantly lowers computational weight, allowing efficient, lightweight algorithms to operate directly on low-power field devices, such as drone flight controllers or inspection tablets (Zhou et al., 2026).

2.3 Structural Constraints and Limitations

Bounding-box designs have two significant drawbacks for structural analysis, despite their high processing speeds:

Coarse Boundaries: Bounding boxes provide only approximate rectangular coordinates. They cannot represent the complex, irregular shapes of actual infrastructure deterioration, such as corrosion patches or jagged concrete cracks (Spencer et al., 2019).

Absence of Quantitative Metrics: Because these models do not trace the precise perimeter of a defect, they cannot directly compute important engineering metrics such as crack width, spalled volume, or total deterioration surface area. As a result, object detection works well for quick asset mapping but is not sufficient by itself for detailed structural reliability assessment (Chen and Omenzetter, 2013). Consequently, while inadequate for accurate structural reliability indexing, single-stage object detection represents the optimal architecture for rapid screening and macro-level asset cataloging over large-scale transit networks.

3. IMAGE SEGMENTATION

Recent work uses pixel-level semantic and instance segmentation for high-precision defect quantification to get beyond bounding-box constraints (Kalfarisi et al., 2020). To trace the precise, irregular boundaries of cracks and spalling, models such as U-Net and Mask R-CNN perform pixel-wise classification. This enables engineers to compute quantitative structural indices, such as total degraded area and real crack width, directly (Parnia Shokri et al., 2022). However, these architectures continue to be extremely sensitive to changes in lighting and environmental noise, and they require large, labor-intensive training datasets (Wang et al., 2026). Despite these data overheads, pixel-wise segmentation remains the uniquely suitable approach for detailed defect measurement where sub-millimeter geometric precision is critical for structural load ratings.

4. VISION-LANGUAGE MODELS (VLMS)

Emerging Multi-modal Vision-Language Models (VLMs) provide dialogue-driven structural diagnostics through text prompts by combining image encoders with large language model decoders (Chen et al., 2025). These frameworks show adaptable zero-shot learning on unfamiliar bridge problems and produce technical reports (Jiang et al., 2025). However, the safety risk of model hallucinations and excessive processing latency still limits their field applications (Wang et al., 2026).

5. COMPARATIVE SYNTHESIS

5.1 Architectural Synthesis and Comparison

There are clear trade-offs between computational weight, data reliance, and targeted application when structural vision frameworks are compared. For real-time asset mapping of massive components like piers and girders on edge hardware, object detection architectures (like YOLO and SSD) are very field-ready due to their minimal computing footprints and little data overhead (Zhou et al., 2026).

On the other hand, semantic and instance segmentation models (such as U-Net and Mask R-CNN) require labor-intensive pixel-level training masks and have high computational weight, but they provide great geometric precision for tracing precise defect boundaries like crack width and spalling area (Kalfarisi et al., 2020; Parnia Shokri et al., 2022).

Although Multi-modal Vision-Language Models (VLMs) offer automated technical reporting and flexible multi-defect evaluation at the cutting edge, their field readiness is still constrained by significant cloud computing requirements and the possibility of diagnostic hallucinations (Chen et al., 2026; Hoier and Ahmed, 2025).

5.2 The Core Hurdle of Data Scarcity

The absence of open-source, standardized public bridge damage datasets is a significant barrier to structural health monitoring (Spencer et al., 2019). The majority of structural datasets are either proprietary or recorded in controlled laboratories, despite the fact that deep learning models need large amounts of heterogeneous data in order to generalize successfully.

Infrastructure in the real world exhibits a great deal of visual variability due to changing weather, ambient lighting, shadows, and debris. Vision models have high error rates on unfamiliar sites due to inconsistent labeling and infrequent collection of these hostile situations in public repositories (Hoier and Ahmed, 2025). Scaling robust inspection AI requires overcoming this data barrier using open-access damage libraries.

6. FUTURE OUTLOOKS AND CONCLUSIONS

6.1 Integrating Edge-AI Drone Platforms into DOT Asset Management Workflows

Department of Transportation (DOT) maintenance workflows could be significantly improved by integrating edge-computing technology on Unmanned Aerial Vehicles (UAVs) and multi-modal vision-language reporting (Liang et al., 2025). Because traditional asset management often depends on manual inspections that take weeks to record and process, it can remain reactive and slow (Agdas et al., 2016).

A future paradigm would replace this approach with a more proactive framework that unifies the CV architectures reviewed in this paper. Aerial platforms could perform real-time edge processing to identify important structural defects during flight by deploying single-stage object detection models on drone flight controllers (Zhou et al., 2026). Where severe anomalies are flag-mapped, localized pixel-wise segmentation models (Section 3) can be dynamically triggered to provide immediate, detailed defect measurement. These visual detections could then be compiled by localized multi-modal systems into standardized natural language condition reports, This bridges the gap between raw pixel analysis and automated report generation, simplifying data flow and helping asset managers prioritize repair investments (Jiang et al., 2026).

6.2 Summary

By reducing the subjectivity and safety risks associated with manual bridge inspections, automated computer vision offers an important advancement for infrastructure maintenance. This review traced the development of vision-based diagnostics across three areas: (1) pixel-level segmentation frameworks for accurate defect quantification, (2) object detection architectures for rapid asset cataloging, and (3) emerging Vision-Language Models (VLMs) for dialogue-driven diagnostics. Although data shortages and environmental noise remain practical field challenges, the combination of edge-AI drone hardware and multi-modal systems is likely to reshape infrastructure lifecycle management.

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LENIS MACHINES INC.: A Profile of Industrial Packaging Automation and Robotics Potential

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ABSTRACT: LENIS MACHINES INC. is a packaging and production machinery company that occupies an important position within the broader automation ecosystem. Its capabilities include the design, manufacturing, and assembling of packaging equipment, with a particular emphasis on customized solutions for complex packaging applications. Its business model extends beyond the sale of individual machines to the delivery of integrated production solutions that support packaging, handling, and end-of-line automation for a wide range of industries. From an academic perspective, the company is best understood as a systems integrator and technology provider whose offerings contribute to manufacturing efficiency, process standardization, and industrial modernization.

1. INTRODUCTION

The contemporary manufacturing sector increasingly depends on automation to improve productivity, product consistency, and operational resilience. In this context, companies such as LENIS MACHINES INC. play a strategic role by enabling firms to transition from labor-intensive processes to semi-automated or fully automated production lines. LENIS positions itself as a provider of packaging and production machinery solutions, with services that support businesses from initial consultation through installation, commissioning, and after-sales support. This end-to-end model is significant because it reduces the technical burden on clients while accelerating adoption of automation technologies..

2. CORPORATE PROFILE

LENIS MACHINES INC. is based in British Columbia and serves clients across North America and international markets. The company's profile suggests a strong emphasis on practical industrial implementation rather than purely theoretical machinery sales. In other words, it offers not only equipment but also the technical framework required to integrate machines into functional production environments. This is particularly important in sectors where packaging quality, hygiene, throughput, and traceability are critical.

From a business standpoint, LENIS can be described as an enabling company. It supports entrepreneurs, small manufacturers, and established producers that require scalable packaging systems. Its approach is especially relevant to firms that may lack the internal engineering capacity to design complete automation lines independently.

For more information about LENIS MACHINES INC. and its solutions, please visit:
https://www.lenismachines.com

3. CORE OFFERINGS

LENIS MACHINES INC. delivers a comprehensive portfolio of advanced packaging and production machinery, with a strong focus on custom-engineered solutions for complex products and innovative packaging formats. Its offerings include systems for:

- Mixing and blending
- Weighing and precision filling
- Bagging and pouch packaging
- Bottling and capping
- Wrapping and sealing
- Cartoning and case packing
- Robotic palletizing and pallet wrapping
- Specialized stick pack, sachet, and flow wrapping systems
- Fully customized packaging machinery tailored to unique product characteristics and innovative packaging requirements

The company's core strength lies in designing bespoke machinery solutions for products that are difficult to handle, such as non free flowing powders, viscous or multi-phase liquids, and irregular or sensitive materials, where standard equipment falls short. LENIS MACHINES INC. works closely with clients to develop innovative packaging systems that meet specific functional, aesthetic, and operational needs.

This broad and flexible capability enables the company to address both primary packaging, where the product is first enclosed, and secondary or tertiary packaging, where products are grouped, boxed, or prepared for logistics. Its adaptability supports a wide range of industries, including food, pharmaceuticals, cosmetics, chemicals, and consumer goods, particularly in applications requiring precision, customization, and innovation.

Demonstrations of selected packaging systems and customized solutions can be viewed here:

https://youtu.be/fBOz1QwCMjg?si=3us0Zf1DymYy4CeN
https://youtu.be/2EmCjbw_b-0?si=fJlmcPLaXOu-vdKx
https://youtu.be/7h0BcMzq2Hc?si=s-YC2HMzZ4oPLcgq
https://youtu.be/0UAh_99NR20?si=zFViMJDl3gNcPjpu

4. INDUSTRY ENGAGEMENT AND EXHIBITIONS

LENIS MACHINES INC. actively participates in major international industry exhibitions to stay aligned with evolving packaging technologies and market demands. The company recently showcased its solutions at Pack Expo Las Vegas in October 2025, one of the world's leading packaging machinery exhibitions, and is scheduled to participate in the upcoming Pack Expo International in Illinois in October 2026. These platforms provide opportunities to demonstrate customized machinery solutions, engage with industry stakeholders, and observe emerging trends in automation and packaging innovation.

Visual documentation of the company's participation at Pack Expo Las Vegas can be accessed at the following links:
https://youtu.be/6QJfXlc7POg?si=uF2HHCHK0ncVUDzu
https://youtube.com/shorts/3Z6czcc9ELg?si=Uugh2Acu0hodnnxN

5. INDUSTRIAL CONTRIBUTION

The importance of LENIS lies in how its systems help improve manufacturing performance. Packaging automation can reduce human error, increase consistency, and improve production speed. It can also enhance workplace safety by reducing repetitive manual handling and exposure to heavy or hazardous materials. For companies in regulated sectors such as food and pharmaceuticals, automation further supports compliance by improving repeatability and traceability.

Another important contribution is scalability. Firms often begin with a single machine, such as a filler or wrapper, and later expand toward integrated production lines. LENIS appears to support this progression by offering modular and customized solutions. This flexibility is valuable because it allows firms to modernize incrementally rather than making a large capital investment all at once.

6. SERVICE AND SUPPORT MODEL

A defining feature of LENIS is its support-oriented service structure. The company emphasizes consultation, installation, commissioning, troubleshooting, and maintenance. This model is essential in industrial automation because even well-designed machines require calibration, process adjustment, and periodic service.

Its support framework also reflects an understanding of operational continuity. Production lines cannot afford prolonged downtime, so responsive technical support is a major competitive advantage. From an academic and industrial perspective, this makes LENIS not merely a machine supplier but a life-cycle partner in production automation.
Engineering education should respond to AI by restructuring curricula and assessments rather than by attempting to disregard the tool. Thus, AI literacy should be embedded across programs, including prompt formulation, verification of AI outputs, bias and uncertainty, data privacy, citation practices, and ethical responsibilities. Hence, students should learn that AI-generated responses are not authoritative unless they are independently checked using engineering principles, standards, experiments, or validated models (UNESCO 2021).

Rapid AI evolution may outpace curriculum updates, and faculty may lack the training or confidence to integrate AI effectively. Assessment strategies should also evolve. In-class problem-solving, oral examinations, live coding, design reviews, laboratory demonstrations, and project-based evaluations can support genuine understanding. Assignments should be redesigned to involve reflection, justification of assumptions, comparison with hand calculations, and transparent documentation of AI usage. Traditional assessments may become less effective; rather than asking only for final answers, educators should evaluate reasoning, verification, interpretation, and communication (Cotton et al. 2024; Kasneci et al. 2023). There is a clear need for new evaluation methods, such as project-based evaluations and oral defences.

Finally, engineering programs should highlight human skills that AI cannot replace, including creativity, judgment, teamwork, ethics, communication, and responsibility for public welfare. The future engineer will not simply be a user of AI tools, but a professional who can decide when AI is appropriate, when its outputs are unreliable, and how to integrate it responsibly into engineering workflows (Holmes et al. 2019; Luckin et al. 2016).

The AI boom has recently disrupted the job market in the tech sector. However, its impact will soon be experienced in various other sectors as well. Students may face increasing uncertainty about future roles, underscoring the need to redefine engineering competence to emphasize adaptability, critical thinking, and effective collaboration with AI systems. In engineering education, this uncertainty underscores the need to redesign curricula to focus on adaptable skills, critical thinking, and the ability to work effectively alongside AI, rather than relying solely on traditional technical competencies.

7. ROBOTICS POTENTIAL

The most compelling future dimension of LENIS MACHINES INC. is its potential role in robotics. As manufacturing evolves, packaging systems increasingly depend on robotic technologies for repetitive, precise, and high-speed tasks. Robot palletizing, automated pick-and-place systems, vision-guided inspection, and collaborative robotic handling are now central to modern production environments.

LENIS is well positioned to participate in this transformation because many of its current solutions already interface naturally with robotics. For example, palletizing systems are often robot-driven, and packaging lines increasingly require robotic synchronization for filling, sorting, boxing, and end-of-line handling. This creates a strong opportunity for the company to move from conventional automation into advanced robotic integration.

Robotics applications relevant to LENIS

• Robotic palletizing for stacking and warehouse preparation. Pick-and-place robots for sorting and transfer operations.
• Vision-based quality inspection for defect detection and package verification. Collaborative robots for flexible small-batch packaging environments.
• Autonomous material handling within smart factories.
• Human-robot interfaces for safer and more adaptive production systems.

These applications are especially important because robotics is no longer limited to large-scale heavy industry. Small and medium-sized enterprises increasingly need affordable robotic solutions that can be deployed in packaging, assembly, and logistics. A company such as LENIS can serve as a bridge between traditional packaging machinery and next-generation robotic manufacturing.

8. CAREER PATH FOR THE NEXT GENERATION

LENIS and companies like it present an attractive career path for the next generation of engineers, technologists, and automation specialists. The field integrates mechanical design, controls, mechatronics, robotics, software integration, and industrial project management. This interdisciplinary nature makes it highly suitable for students and young professionals seeking careers with strong technical depth and practical impact.

Potential career roles include:

• Machine design engineer.
• Automation engineer.
• Controls and instrumentation specialist.
• Robotics engineer.
• Manufacturing systems integrator.
• Field service and commissioning engineer.
• Process automation consultant.
• Mechatronics technician.

For younger generations, this sector offers a compelling combination of innovation and societal relevance. Robotics and automation support food security, supply-chain efficiency, industrial competitiveness, and sustainable manufacturing. As global industry continues to digitize, the demand for professionals who can design, program, maintain, and optimize intelligent production systems will continue to grow.

9. CONCLUSION

LENIS MACHINES INC. can be understood as a packaging automation company with strong industrial relevance and significant future potential in robotics. Its current value lies in its ability to provide integrated machinery solutions, technical support, and scalable production systems. Its future potential lies in expanding these capabilities into robotic automation, smart factory integration, and advanced manufacturing services.

From an academic standpoint, the company is a useful example of how industrial machinery firms contribute to economic development, workforce transformation, and technological modernization. Its evolution toward robotics could make it an especially attractive model for the next generation of engineers seeking meaningful, future-oriented careers in automation and intelligent manufacturing.

Technology Convergence of Hydrokinetic Energy Conversion Systems

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ABSTRACT: Hydrokinetic energy conversion systems are turbine-generator based electromechanical systems that harness electrical power from free-flowing streams commonly found in rivers, canals, dam tailraces, tidal channels and marine currents. This concept differs from hydroelectric power plants or tidal barrages where large dams or other infrastructure are required. Hydrokinetic devices are also referred to as tidal turbines, marine current turbines, in-stream devices or river turbines - some of which are being used as brand or device names by some industrial proponents. This article provides a broad overview of this class of technology and introduces the readers to both the fundamentals and applied concepts - enabling them to explore further.

1. INTRODUCTION

Since the dawn of time, mankind has relentlessly endeavored to harness the power from moving waters whether its for transportation, agriculture or for electric power generation. What used to be humble waterwheels evolved into run-of-the-river micro-hydro plants at the turn of the century. In modern electric power systems, large-scale hydroelectric generation produces thousands of megawatt of renewable power. This progression continues even today.

The class of hydrokinetic energy conversion pertains to utilization of kinetic energy in river streams, man-made waterways, tidal flows and ocean currents in generating electricity. This emerging field of renewable energy exploration has seen a strong resurgence over the last two decades driven by the advancements in multiple fields, namely, electro-mechanical devices, power electronic conversion and offshore technologies. This has led to the development of a plethora of concepts, many of which advanced to trials, pilot projects, near-commercial deployments achieving varying degrees of success.

In a conventional hydroelectric plant, the stored static energy of water (often referred to as the 'head') in a reservoir behind the dam is used to run the turbomachinary downstream. In contrast, hydrokinetic energy conversion systems (HECS) are generally constructed without significantly altering the natural course of the water. To scale up the production, often an array of devices is contemplated similar to wind farms. While modularity and scalability are attractive features, it is also understood that hydrokinetic systems would be more environmentally friendly when compared with conventional hydroelectric plants. This is simply because the footprint is small and modular deployment can be pursued to scale up the plant size. Figure 1provides a conceptual outline of a hydrokinetic system.

As highlighted in the author's previous work [1][2], early prototypes of hydrokinetic systems were meant for generating electricity for remote and rural communities (see Figure 2}. Many of these were developed in the 60s and 70s [3][4][5][6][7][8]. During the last two decades, a significant number of new devices, companies and consortia have come into the picture - advancing the technology to a near-commercial stage[9][10][11][12].

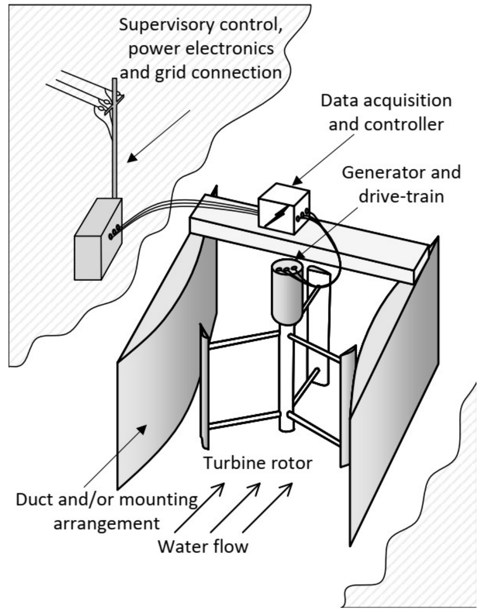


Figure 1: Outline of a hydrokinetic energy conversion system (HECS)

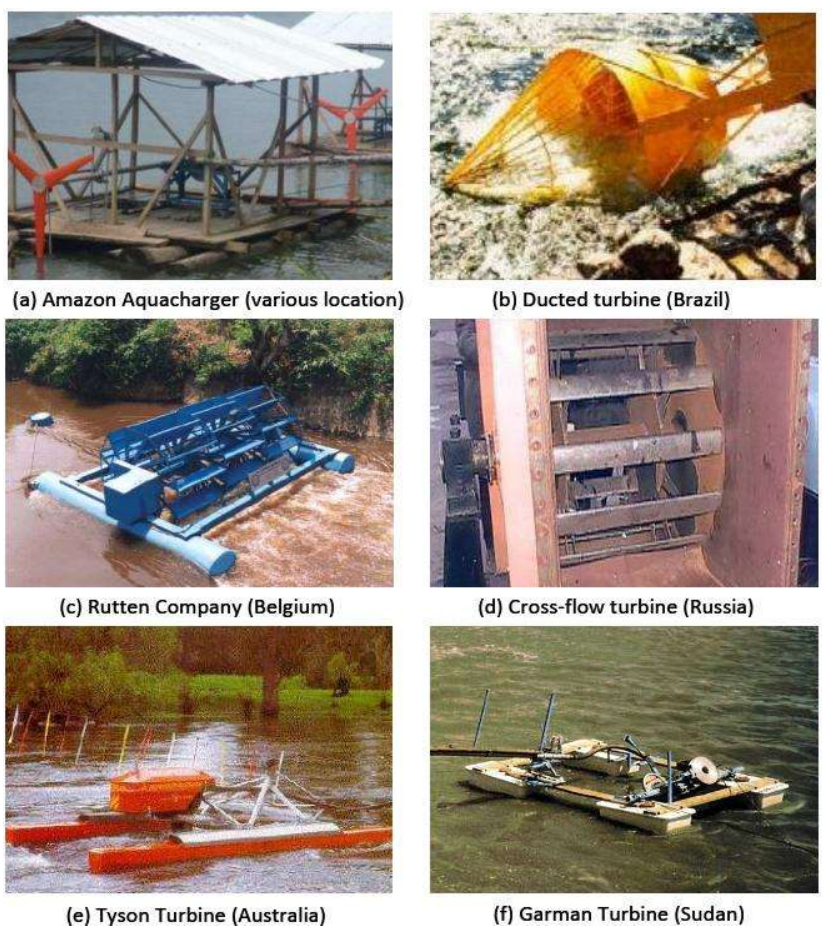


Figure 2: Early prototypes of HECS

While the interest in this field is obvious, hydrokinetic energy generation is yet to reach a commercial level. Despite the abundance of concepts and pilot-projects, only a few devices have managed to reach real-world trials. Some of the devices - along with their developers, have ceased to exist today. On the other hand, several new technologies, albeit fundamentally similar in concept, have taken the center stage and continue to show promise.

2. CONVERSION SCHEMES

The energy flux contained in a fluid stream is directly related to its velocity and density. The effective cross-sectional area of the device is also a key factor. While there is a theoretical ceiling of how much power can be harnessed by a device, the conversion efficiency of the hydrodynamic, mechanical and electrical subsystems collectively reduces the overall output. While rotary systems such as horizontal and vertical axis turbines are generally considered as prime choices for such schemes, other non-turbine approaches are also possible. A brief description of twelve (12) concepts categorized in two broader classes (turbine/non-turbine) is given below:

Turbine systems

- *Horizontal (Axial):* Often called 'axial turbines', these devices are characterized by their rotor axis which is in-line with the incoming water (e.g. [13]) and have an appearance of an inverted wind turbine.
- *Vertical:* Devices that have a cylindrical shape with its axis of rotation vertical to the incoming water (e.g. [14]). These are often called 'egg-beater' type turbines.
- *Cross-flow:* Devices that have a cylindrical shape with its axis of rotation horizontal to the water surface (e.g. [15]). These devices have a general appearance of a water-wheel.
- *Venturi:* Devices where a venturi tube creates a pressure gradient forcing the incoming water to gain speed and run a turbine (e.g. [16]).
- *Gravitational Vortex:* Devices where the flow of water is diverted into a channel that artificially induces a vortex which in turns operates a turbine (e.g. [17]).
- *Archimedes Screw:* Devices that have a helical surface around a vertical shaft and diverts the incoming water in an upwards spiral impinging on a turbine (e.g. [18]).

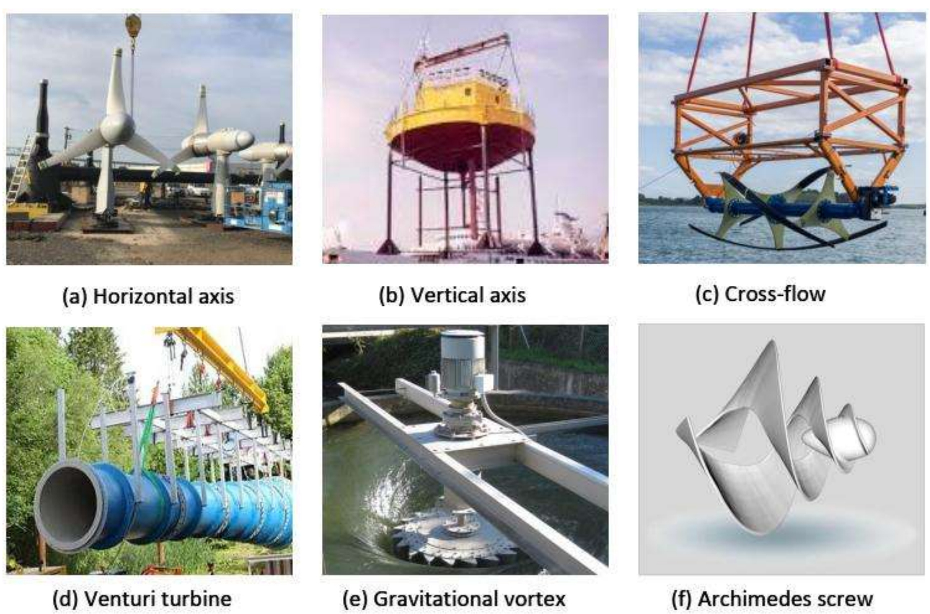
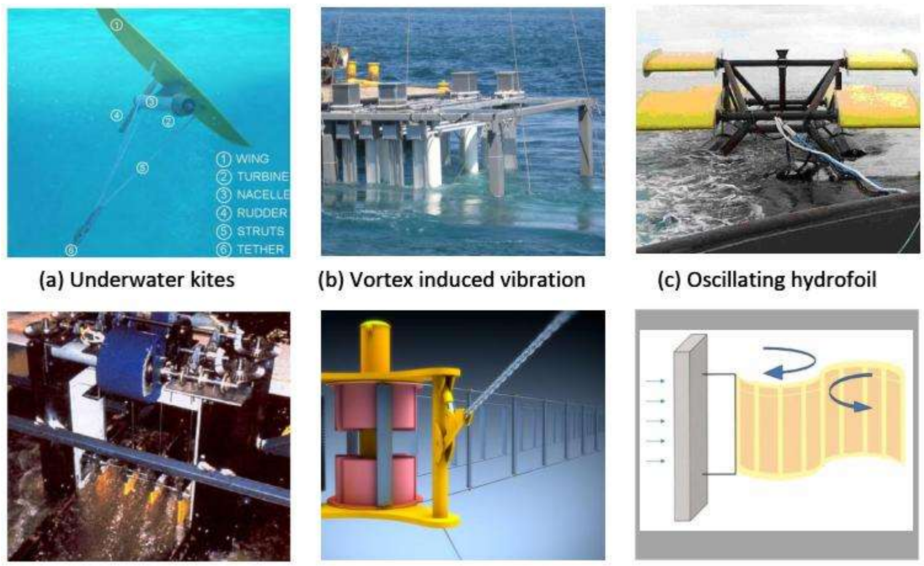


Figure 3: Turbine systems

Non-turbine systems

- *Underwater Kites:* Devices that are tethered to the seabed and move underwater similar to a "kite" producing power through a turbine mounted on the moving structure [19].
- *Vortex induced vibration:* Devices that employ vibrations resulting from vortices forming and shedding on the downstream side of a bluff body placed in a current [20].

- *Oscillating hydrofoil:* Devices that harness the vertical oscillation of hydrofoils and pump pressurized fluids to rune turbines [21]. A variant of this class includes biomimetic devices for energy harvesting [22].
- *Flutter Vane:* Devices that are based on the principle of hydroelastic resonance in free-flowing water [23].
- *Tidal sail:* Devices that employ drag motion of circularly moving sheets of foils placed in a water stream [24].
- *Piezoelectric:* Devices that utilize piezo property of polymers that produce electricity due to pressure induced by incoming water stream [25].



(a) Underwater kites (b) Vortex induced vibration (c) Oscillating hydrofoil

(d) Flutter vane (e) Tidal sail (f) Piezoelectric

Figure 4: Non-turbine systems

At present, various turbine concepts and designs are being widely pursued (Figure 3) while the non-turbine systems (Figure 3) are mostly at the proof-of-concept stage (with some exceptions).

Two main areas where hydrokinetic devices can be deployed: (a) tidal-current and (b) river-stream. Energy from subsea ocean currents is another niche area where the flow is unidirectional, as opposed to bidirectional tidal flows. In addition to these, other areas of application include man-made channels, irrigation canals and industrial outflows. While all hydrokinetic devices operate on the same conversion principles regardless of their areas of application, a set of subtle differences may appear in the forms of design and operational features.

3. TECHNOLOGY SURVEY

The following section provides a survey of hydrokinetic energy conversion technologies, and sheds light on their diversity, progression, trends and convergence. Being an evolving and dynamic field, it is nearly impossible to provide an exhaustive and comprehensive survey. With a general focus on applied technologies that have demonstrated inclination toward commercialization, this survey explored nearly 100+ systems. Due to availability of limited information for many devices, mostly the primary conversion hardware and their peripherals (rotors, ducts, placement method in a stream, etc.) are evaluated. The information gathered along the process is organized through the following categories:

- **Application:** In the previous section, various areas of application for hydrokinetic devices have been identified. This discussion is carried forward into the survey by categorizing the potential use of a given device into (a) tidal-current (for tidal and ocean current resources) (b) river-stream (for free-flowing/zero-head rivers), and (c) multi-application (river, tidal, and other applications). While the information disseminated through the relevant technology developer, research institute, or public-domain document has been the basis of this classification, several ambiguous cases have been considered as ‘Multi-application’.

- **Technology type:** Considering the discussion presented earlier, all of the 76 devices or concepts have been attributed to one of the ten (10) conversion schemes. However, further division into 'turbine' or 'non-turbine' systems has not been carried out.

- **Duct:** Ducts are engineered structures that elevate the energy density of a water stream as observed by a hydrokinetic converter. Considerations for these devices is of high significance primarily because of two opposing reasons (a) potential to augment the power capacity and hence reduce the cost of energy (b) lack of confidence as far as their survivability and design/demonstration are concerned. In this survey, attempts were made to identify whether a given scheme is considered for duct augmentation (unknown cases were identified separately) or not.

- **Placement:** The method of placement of a hydrokinetic device, in relation to a channel cross-section, is a very significant component for two basic reasons:
    - The energy flux in the surface of a stream is higher than that of a channelbottom. In addition, this quantity takes diverse values depending on the distance from the shore and channel-geography. Therefore, water velocity has a highly localized and site-specific 3-dimensional profile and rotor positioning against such variations will dictate the amount of energy that can be effectively extracted.
    - Competing users of the water stream (recreational boats, fishing vessels, bridges & culverts, etc.) would essentially reduce the effective usable area for a turbine installation.

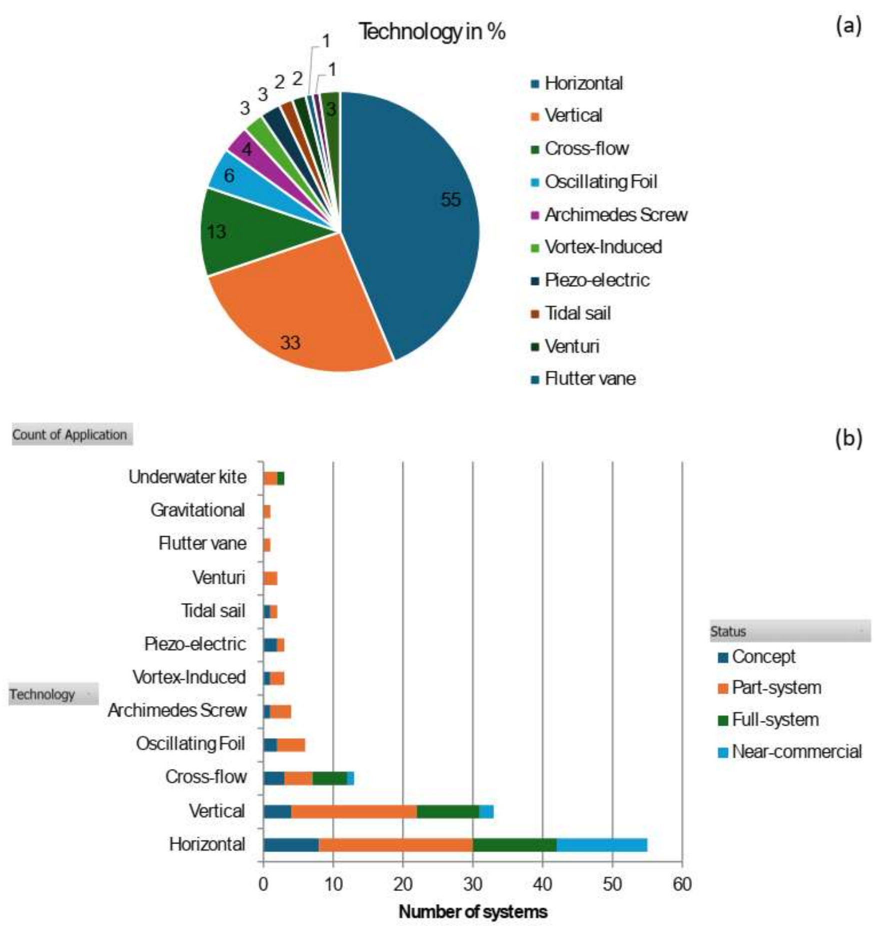


Figure 5: Technology survey (a) percentage of total (b) technology progression

While both vertical and axial turbines have long been considered as primary choices for hydrokinetic energy conversion, a number of unconventional concepts (such as, vortex induced vibration, and piezoelectric conversion) have appeared recently. Several early river turbine prototypes were deployed and operated from late

70's to late 90's until these were eventually decommissioned. Various non-turbine concepts (namely, oscillating hydrofoil and piezoelectric conversion) had gained good attention in the past. However, their present status of development is unknown. Analyzing the modern-day history of hydrokinetic energy conversion, it can be clearly noticed that the present decade has so far seen the greatest level of research and development initiatives. These efforts have enveloped a multitude of technological concepts as well as diverse fields of applications where hydrokinetic technologies may prosper in future (see Figure 5).

4. SUMMARY

In this paper, the state of the hydrokinetic energy conversion technologies has been revisited with an emphasis on indicating the current trends in research and development initiatives. The major conclusions that can be derived from the discussions presented earlier are:

- Except for some early commercial systems (small-scale remote power generation from river streams), most of the technologies are at the proof-of-concept or part-system R&D stage.
- A number of novel schemes (such as, piezo-electric, biomimetic and vortexinduced-vibration) have surfaced in recent times, in addition to the continued progress on classical hydrokinetic energy conversion approaches (vertical, axial turbines, etc.).
- In the presence of a wide variety of terminologies attributed to the fundamental process of kinetic energy conversion from water streams, the term 'Hydrokinetic' energy conversion can be used as long as sufficient caveats are given for diverse fields of application such as, rivers, artificial channels, tides, and marine currents.
- In addition to the specific focus on river or tidal current conversion, strong emphasis is given to technologies that may serve both of these areas as well as other potential resources (such as, man-made canals, irrigation channels, and industrial outflows).
- While both axial and vertical axis turbines are being developed for hydrokinetic energy conversion, considerations for duct usage have seen higher preference for the latter class.
- Various options for turbine placement with respect to a channel cross-section (bottom, floating, or near-surface/fixed) are being given almost equal emphasis. However, axial turbines are mostly being considered for placement at the bottom of a channel, whereas vertical turbines are being designed for either floating or near-surface mounting arrangements.
- Recent technological advancement and project-development initiatives clearly indicate a rejuvenated interest in the domain of hydrokinetic energy conversion.

As the hydrokinetic technologies evolve over time, new solutions emerge, and old concepts resurface/disappear, the review presented in here may need to be re-evaluated. However, the major observations made in this section may still appear useful in identifying the technology trend being followed in this field of energy engineering. To conclude this discussion, it can be stated that hydrokinetic energy technologies are emerging as a viable solution for renewable power generation and significant research, development, and deployment initiatives need to be embarked upon before realizing true commercial success in this sector.

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Literature Review of AI-Driven Structural Health Monitoring and Damage Assessment: From Sensor-Based Systems to Vision-Language Models

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ABSTRACT: Structural damage assessment is essential for ensuring the safety, reliability, and longevity of civil infrastructure. Traditional inspection methods often rely on manual visual assessments or sensor-based structural health monitoring (SHM) systems, which can be time-consuming, costly, and difficult to scale. Recent advances in artificial intelligence (AI) have enabled automated damage assessment frameworks that leverage computer vision, deep learning, vision-language models (VLMs), and large language models (LLMs) to analyze structural damage and support engineering decision-making. This literature review examines the evolution of AI-based structural damage assessment frameworks, ranging from conventional sensor-driven SHM approaches and convolutional neural network (CNN)-based damage detection systems to emerging multimodal architectures that combine visual understanding with language-based reasoning. Particular attention is given to recent VLM- and LLM-assisted frameworks, including visual question-answering systems, knowledge-augmented diagnostic models, and rubric-based assessment approaches for infrastructure inspection.

1. INTRODUCTION

Structural health monitoring is the continuous monitoring of a structure to ensure its integrity. A core part of SHM is structural damage assessments done by licensed engineers who determine the safety and stability of a structure. SHM provides realtime, continuous data, ensuring safety and risk mitigation, optimized maintenance and cost efficiency as well as possibly extending the lifespan of the structure (Chen and Omenzetter 2013; Hassan et al. 2023). When it comes to public safety and risk mitigation, structural damage assessments can detect structural fatigue or cracks before they lead to collapse, thereby ensuring human safety (Hassan et al. 2023; Silva-Campillo et al. 2023). Periodic monitoring of structures also improves efficiency and optimizes maintenance. Knowing exactly where the structural problem lies can allow engineers to avoid unnecessary repairs as well as minimize costly emergency shutdowns (Chen and Omenzetter 2013; Costin et al. 2023). Tracking the condition of a structure also allows the structure to be well maintained and will show engineers where exactly to reinforce the structure in order to expand its lifespan (Harmanci et al. 2016; Costin et al. 2023).

Although structural health monitoring provides significant benefits, traditional manual inspection approaches are constrained by the subjective nature of human evaluation. Human inspection also faces practical challenges. Hidden or inaccessible damage, such as internal cracks or foundation movement, may not be visible during roputine assessment. If such damage is missed, the evaluation may lead to an incorrect and potentially dangerous outcome. The sensory capabilities of the human eye may not be sufficient for evaluating some internally damaged structures. Manual monitoring of also relies heavily on the individual's experience and judgement, which can lead to inconsistency or human error (Agdas et al. 2016; Quqa et al. 2025).

To address the challenges associated with human evaluation, alternative approaches have been developed, including sensor-based SHM systems and vision-based computational methods (Hoskere et al. 2018; Quqa et al.

2025). More recently, advances in artificial intelligence, particularly vision models and large language model (LLM)-based reasoning systems, have enabled more automated and scalable approaches to structural damage assessment (Liang et al. 2025; Jiang et al. 2025; Chen et al. 2026). This paper reviews recent literature from the past decade, focusing on AI-driven and LLM-integrated frameworks for structural health monitoring and automated damage assessment.

2. METHODS

The Google Scholar (https://scholar.google.com/) website was used to identify papers for this review. Keywords such as "artificial intelligence", "LLM", "Structural health monitoring", "SHM", "damage assessment" and "VLM" were used to find papers on automated structural health monitoring methods. Approximately 20 papers primarily between 2016 and 2026, were selected based on relevance to AI-based or automated structural health monitoring and damage assessment. Papers were included if they focused on structural or infrastructure applications of AI, machine learning, computer vision, or sensor-based monitoring systems. Preference was given to recent studies that proposed novel AI methodologies or demonstrated practical applications for structural damage detection, assessment, or monitoring.

A summary table has been added to improve readability and facilitate comparison across studies. The table outlines the AI techniques, applications, key strengths, and limitations of each reviewed work.

Table 1: Summary of Reviewed Studies on AI-Based Structural Health Monitoring

Study	AI Technique	Application	Strengths	Limitations
Agdas et al. (2016)	Structural Health Monitoring systems (sensor + visual inspection comparison)	Bridge condition assessment	Demonstrates benefits of SHM over manual inspection	Not AI-based; limited automation
Chen & Omenzetter (2013)	Reliability assessment framework using SHM data	Bridge reliability evaluation	Probabilistic structural safety modeling	Requires extensive sensor data; no ML
Harmanci et al. (2016)	Autonomous strain-based monitoring system	Lifecycle structural monitoring	Real-time autonomous monitoring framework	Limited scalability and generalization
Hoskere et al. (2018)	Deep CNN (computer vision)	Structural inspection and damage detection	Early deep learning application; strong visual detection	Requires large labeled datasets
Silva-Campillo et al. (2023)	Review of SHM sensor systems	Marine structure monitoring	Comprehensive system overview	Focused on marine domain only
Hassan et al. (2023)	SHM evaluation frameworks	Bridge assessment systems	Summarizes SHM practices	Limited AI integration
Costin et al. (2023)	Digital twin frameworks	Bridge SHM and maintenance	Integrates existing SHM technologies	Still reliant on traditional data pipelines
Chen et al. (2026)	Large Vision-Language Models (VLMs)	Post-disaster damage assessment	Automated reporting + interpretation	Early-stage validation
Chen et al. (n.d.)	Vision-Language Model	Bridge inspection	Multimodal reasoning for inspection	Limited dataset validation
Jiang et al. (2025)	Large Language Model (LLM)	Earthquake damage assessment	Natural language reasoning for damage reports	Needs structured visual inputs
Jiang et al. (2026)	Unified VLM framework	Post-earthquake building damage	Multitask learning improves robustness	Computationally expensive
Liang et al. (2025)	Lightweight VLM (DL-VLM)	Bridge health diagnosis	Efficient and deployable model	Reduced accuracy vs large models
Quqa et al. (2025)	Survey (regional SHM methods)	Bridge monitoring at scale	Roadmap for climate-aware SHM	Not a technical method
Tan (2025)	Time-series neural networks	Sensor-based SHM optimization	Strong signal processing and inference	Limited visual integration
Wang et al.	Digital twin frameworks	SHM system	Lifecycle monitoring	Implementation

(2025)		integration	integration	complexity
Wang et al. (2026)	Segmentation + VLM	Satellite-based damage detection	High interpretability	Depends on image resolution
Xiao et al. (2025)	Vision-Language foundation model	Road damage understanding	Benchmark + large-scale dataset	Early-stage foundation model
Yang et al. (2025)	LLM-based framework (WaveformerNet-Mixer-LLM)	Bridge damage identification	Hybrid AI architecture improves reasoning	Limited real-world deployment
Zhou et al. (2026)	Lightweight SSD-based CNN	Concrete crack detection	Fast and efficient detection	Limited semantic reasoning

3. DISCUSSION

The reviewed literature showed a clear evolution in structural health monitoring (SHM) and damage assessment methods. Traditional SHM systems primarily relied on sensor-based approaches, including strain gauges, vibration monitoring, and reliability-based analyses (Chen and Omenzetter 2013; Harmanci et al. 2016). These methods provide continuous structural data and can detect changes in structural behavior over time; however, they often require extensive sensor installation, maintenance, and expert interpretation (Chen and Omenzetter 2013; Quqa et al. 2025).

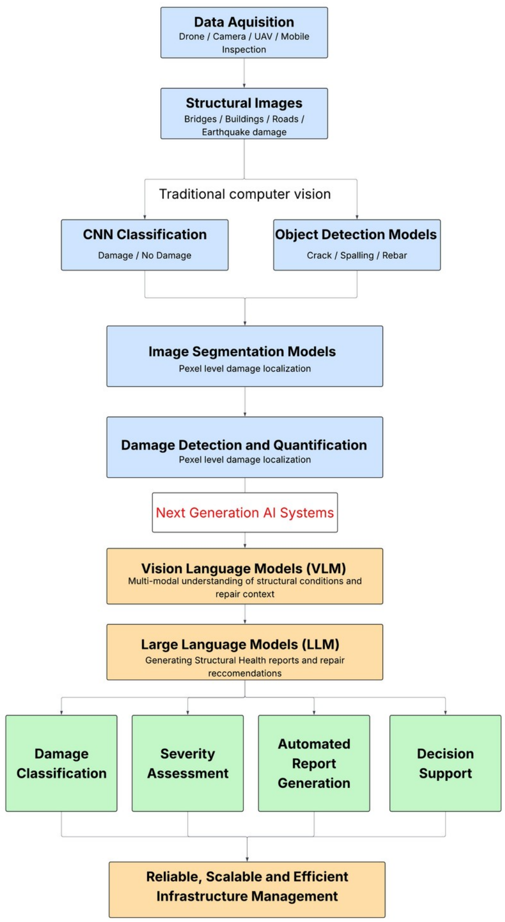
Recent advances in artificial intelligence have led to increased use of computer vision techniques for automated inspections. Studies utilized convolutional neural networks (CNNs), object detection algorithms, and image segmentation models to identify structural anomolies such as cracks and earthquake damage from images (Hoskere et al. 2018; Zhou et al. 2026; Wang et al. 2026). Compared to traditional evaluation methods, these approaches can reduce inspection time while improving consistency and scalability (Hoskere et al. 2018; Chen et al. n.d.).

More recently, researchers have begun incorporating vision-language models (VLMs) and large language models (LLMs) into structural damage assessment workflows. Unlike vision models that focus only on defect detection, VLM-based systems can combine visual information with reasoning, allowing for automated damage classification, report generation, and decision support (Chen et al. 2026; Jiang et al. 2025). Frameworks such as DL-VLM and related approaches demonstrate the potential for AI to assist engineers throughout the inspection process, rather than solely finding defects (Liang et al. 2025; Chen et al. n.d.; Jiang et al. 2026).

Despite the promising results reported across the literature, several challenges remain. Many AI approaches rely on large, high-quality datasets that may not be readily available for all infrastructure types (Xiao et al. 2025; Jiang et al. 2026). The reliability of AI-generated evaluations also remains an important concern, especially in safety-critical applications where engineering decisions can have significant consequences (Chen et al. 2026; Hoier and Ahmed 2025). Moreover, few studies have fully integrated sensor-based monitoring, computer vision, and language-based reasoning into a unified framework (Costin et al. 2023; Wang et al. 2025).

Overall, the reviewed literature indicates a clear transition from traditional sensor-driven monitoring toward increasingly automated AI-based structural health monitoring systems (Quqa et al. 2025; Wang et al. 2025). While this shift demonstrates strong potential for improving inspection efficiency and scalability, several practical challenges must be addressed for real-world deployment. Future research should prioritize the development of robust multimodal data fusion frameworks that integrate sensor measurements, computer vision outputs, and language-based reasoning into a unified decision-making pipeline. In addition, the lack of standardized benchmark datasets remains a critical limitation, as current studies are often evaluated on task-specific or non-comparable datasets, restricting reproducibility and cross-method evaluation. Establishing large-scale, diverse benchmarks covering multiple structural types, damage conditions, and environmental settings would significantly improve model generalization and comparability. Finally, although VLM- and LLM-based approaches show promise for automated reporting and decision support, further work is needed to ensure their reliability, interpretability, and computational efficiency in field deployment scenarios, particularly under domain shift and safety-critical inspection conditions (Chen et al. 2026; Hoier and Ahmed 2025; Costin et al. 2023).

Figure 1 shows the evolution of artificial intelligence methods for structural damage assessment. Traditional computer vision approaches, including CNN classification, object detection, and image segmentation, focus primarily on identifying and localizing structural defects from inspection images (Hoskere et al. 2018; Zhou et al. 2026). Recent developments integrate Vision-Language Models (VLMs) and Large Language Models (LLMs), enabling multimodal reasoning that supports automated damage classification, severity assessment, report generation, and maintenance decision-making, thereby transforming defect detection into comprehensive intelligent inspection workflows (Liang et al. 2025; Chen et al. 2026; Jiang et al. 2026).



CONCLUSION

Structural health monitoring plays a critical role in maintaining the safety and longevity of civil infrastructure. This review examined recent developments in AI-based structural damage assessment, including sensor-driven monitoring systems, computer vision techniques, vision-language models, and digital twin frameworks. The literature demonstrates a clear trend toward greater automation, with modern AI systems increasingly capable of detecting, classifying, and interpreting structural damage. While these technologies show significant promise for improving inspection efficiency and reducing reliance on manual assessments, challenges related to data availability, model reliability, and interpretability remain. Continued research is needed to address these limitations and to develop integrated systems that combine multiple sources of structural information. As AI technologies continue to advance, they are expected to play an increasingly important role in structural health monitoring and infrastructure management.

Figure 1. Evolution of artificial intelligence methods for structural damage assessment.

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The evolving paradigm of weather forecasting in the era of artificial intelligence

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ABSTRACT: The advent of AI-based weather prediction (AIWP) models is transforming the weather forecasting enterprise. While these deterministic data-driven models improve global verification scores compared to traditional physics-based numerical weather prediction (NWP), they tend to produce smoother forecasts affecting their ability to predict high-impact weather events at the local scale and, among other limitations, may also struggle with out-of-distribution extremes. As a result, they cannot yet replace physics-based models. A hybrid approach combining AI and physical modeling offers a promising path forward, leveraging the strengths of both methodologies. In this context, Environment and Climate Change Canada has developed a spectral nudging-based hybrid approach that constrains large-scale atmospheric patterns using AIWP predictions while allowing fine-scale dynamics to evolve according to physical laws, yielding an improvement in forecast predictability of approximately 12–24 hours.

1. INTRODUCTION

1.1 Physics-based weather models

For many decades, the backbone of operational weather forecasting has been numerical weather prediction (NWP) models, which are grounded in the fundamental laws of physics. In general, these models contain a dynamical core that solves the nonlinear partial differential equations governing the resolved-scale dynamical and thermodynamical processes of the atmosphere on a computational grid representing a discretized version of the continuous physical world. The solutions produced by the dynamical core are subsequently combined with bulk tendencies from parameterized physical processes, which represent unresolved and subgrid-scale phenomena that cannot be explicitly captured by the model equations or the discrete grid resolution. The NWP model that is at the heart of all operational NWP systems at Environment and Climate Change Canada (ECCC) is the Global Environmental Multiscale (GEM) model (Girard et al. 2014).

To produce a forecast, any model, whether NWP or AIWP, must first be initialized with the best possible estimate of the current atmospheric state, commonly referred to as the “analysis”. Because the atmosphere is chaotic and sensitively dependent on initial conditions, the accuracy of this initial state is critically important. Sophisticated data assimilation (DA) systems are therefore employed to combine real-world observations, such as those from weather stations, radiosondes, satellites, and aircraft, with a previous short-range forecast from an NWP model, given that there are not enough observations to deduce a complete and accurate estimate of the state of the atmosphere from observations alone. Through this process, which demands enormous computational resources, DA produces an analysis that represents the most physically consistent and accurate estimate of the atmospheric state at a given time.

1.2 AI-based weather models

In contrast to traditional NWP models, AI-based weather prediction (AIWP) models introduce a fundamentally different paradigm. These models in general rely on some form of deep neural network, and rather than explicitly encoding physical laws and numerically integrating governing equations forward in time, they learn atmospheric evolution directly from large volumes of historical weather data, most commonly *reanalysis* datasets (Lam et al. 2023; Bi et al. 2023).

Similar to operational analyses, reanalyses are also produced using data assimilation. However, unlike real-time analyses, reanalyses are generated retrospectively by consistently combining historical observations, often spanning multiple decades, with forecasts from an NWP model and the underlying DA system remaining fixed. This leads to a temporally consistent reconstruction of past weather and climate states. Although research is ongoing to develop AI-based weather models trained directly on observations, current AIWP models that rival or surpass state-of-the-art NWP models in standard accuracy metrics are almost invariably trained on reanalysis data and therefore rely on physics-based models. The most widely used dataset is ERA5 reanalysis (Hersbach et al. 2020) produced by the European Centre for Medium-Range Weather Forecasts (ECMWF).

As of today, cutting-edge deterministic AIWP models therefore do not eliminate the role of physics but instead change how it is incorporated into the forecasting system. In NWP models, physical laws are explicitly formulated and numerically integrated forward in time, whereas in AIWP models, physical relationships are implicitly learned through representations derived from reanalysis. As a result, these models strongly depend on the quality, coverage, and representativeness of the training data.

At ECCC, one such deployed AIWP model is GEML (Global Environmental eMuLator), built on the open-source GraphCast model by Google DeepMind (Lam et al. 2023). The model has been trained from scratch at ECCC using ERA5 reanalysis and fine-tuned with higher resolution operational global analyses from ECMWF and ECCC.

2. AIWP VS NWP: RELATIVE STRENGTHS AND WEAKNESSES

The main strengths of deterministic AIWP models are their computational efficiency and forecast accuracy. These models can generate forecasts, often referred to as inference, orders of magnitude faster than traditional physics-based models. Research at ECCC has shown that AIWP models can outperform physics-based NWP models at planetary and synoptic scales (larger than 2,000 km), particularly for medium- to long-range forecasts (beyond day 3 of a 10-day global forecast). However, at these longer lead times (beyond day 3), deterministic AIWP forecasts generally suffer from lack of fine-scale detail necessary to realistically represent weather extremes at local scale. Although probabilistic AIWP forecasts, such as those generated with generative AI models, do not suffer from fine-scale smoothing, they invariably sacrifice individual forecast accuracy for gains in ensemble forecast reliability – similarly to probabilistic NWP models. In contrast, deterministic NWP models are generally better at capturing realistic small-scale details than their AIWP counterparts. However, at longer lead times, large synoptic scales predicted by NWP models can suffer from considerably larger error, mostly due to nonlinear upscale error propagation from finer scales that lose predictability due to the chaotic nature of the atmosphere.

The tendency of deterministic AIWP models to produce spatially smoother forecasts is closely linked to their training objective, namely the loss function they are designed to minimize. Most deterministic AIWP systems are trained using mean squared error (MSE), which encourages the models to predict the mean state of the distribution and avoid the double penalties associated with misplaced weather features. Therefore, as finer scales quickly lose predictability with increasing lead time, the corresponding forecasts from AIWP models tend to become overly smooth to reduce the average prediction error. This may also explain their higher large-scale accuracy at longer lead times.

Part of the computational advantage of AIWP models stems from their limited range of predicted variables. These models are typically trained only on fields available in the reanalysis dataset, while predicting non-analyzed variables often degrades performance. In addition, incorporating the full suite of prognostic variables required for operational NWP, such as cloud and precipitation types, remains computationally unfeasible with current AI architectures. Temporal resolution is another limitation, as most global AI models produce forecasts at 6-hour intervals (Lam et al. 2023; Bi et al. 2023), much coarser than those of physics-based NWP models.

Another important limitation is that AIWP models largely learn from and interpolate between the weather states represented in their training datasets. Consequently, when confronted with out-of-distribution atmospheric states, they may produce larger errors than physics-based models. Studies have shown, for example, that AIWP models fail to learn about strong tropical cyclones (TCs) when their training dataset excludes category 3-5 TCs (Sun et al. 2025). More recent work has also demonstrated that deterministic AIWP models perform poorly for record-breaking extreme events, often underpredicting the intensity and frequency of temperature and wind speed extremes (Zhang et al. 2026). These findings suggest that current deterministic AIWP systems may have a limited ability to generalize and extrapolate beyond the range of conditions encountered during training. Finally, because AIWP models are not explicitly constrained by physical laws, the physical realism of their predictions may fail when evaluated through *falsification* (Ben-Bouallègue 2026), an approach that assesses forecasts for potential violation of physical principles. For example, AIWP models may fail to consistently represent fundamental physical relationships such as geostrophic balance (Bonavita 2024) and can even generate unphysical artifacts, including precipitation without clouds or with physically impossible negative values (Moldovan et al. 2025).

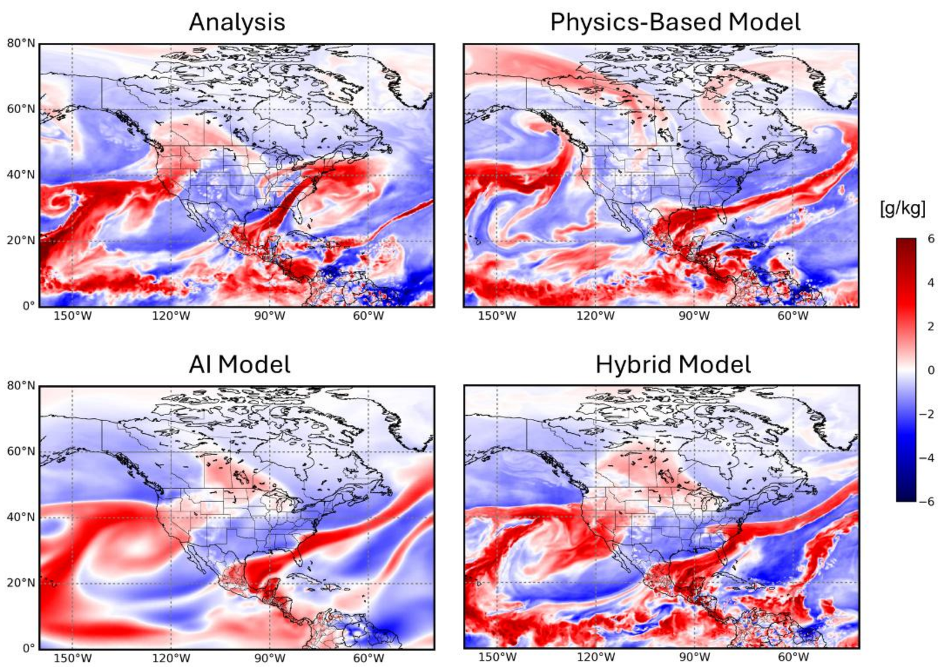

Figure 1. Atmospheric moisture forecasts from three different weather models over North America at 7:00 pm EDT on 1 February 2025 (forecast day 10), during a significant atmospheric river event impacting northern California. The colours represent moisture anomalies, indicating unusually dry (blue) or moist (red) air at the 700 hPa level. ECCC's operational analysis, representing the best estimate of the atmospheric state at the same valid time, is also shown for reference.

3. HYBRID AIWP-NWP MODELLING: THE BEST OF BOTH WORLDS

Based on these insights, a natural question arises: can a hybrid modeling approach combine the strengths of both paradigms? The objective is to achieve the large-scale accuracy of AI-based models while retaining the fine-scale detail represented in physics-based models and generating the full range of predicted variables that operational meteorologists rely on. This motivation led to the development of a new hybrid modeling framework at ECCC, among the first of its kind (Husain et al. 2025).

At its core lies the physics-based GEM model. During simulation, the large-scale weather patterns predicted by GEM, involving spatial scales larger than approximately 2,500 km, are gradually adjusted toward the predictions of the AI-based GEML model. This adjustment mechanism is known as *spectral nudging*, in which large-scale corrections are obtained by computing the differences between the meteorological fields predicted by GEM and GEML, followed by the application of a spectral filter to isolate the scales of interest.

More specifically, spectral nudging is applied to the solution of GEM's adiabatic and inviscid dynamical core at every model time step. The nudged solution is then passed to the physical parameterization schemes, which compute the physical tendencies required to obtain the final model state for that time step. As a result, the large-scale components of GEM evolve toward those predicted by GEML, while the smaller-scale structures that are critical for weather extremes, such as heavy precipitation and severe storms, remain free to evolve in accordance with GEM's established physical and mathematical formulations.

This hybrid modeling approach based on spectral nudging leads to substantial improvements in forecast accuracy, along with a predictability gain of approximately 12–24 hours, depending on the season (Husain et al. 2025). In practical terms, this means that the accuracy of a day-6 forecast from the hybrid model can be comparable to that of a day-5 forecast from the standalone physics-based GEM model. Improvements of this magnitude in operational weather prediction typically require 7–10 years of research and development, whereas the integration of AI enabled these gains to be achieved in less than two years.

Figure 1 illustrates the characteristics of NWP, AIWP, and hybrid weather models using atmospheric moisture forecasts during a significant atmospheric river event affecting northern California. ECCC's operational analysis is shown in the top-left panel. It represents the best estimate of the atmospheric state. For the different weather models, forecasts valid at day 10 are presented.

The top-right panel in Fig. 1 shows the forecast from the physics-based GEM model. It captures substantial fine-scale detail, including sharp and localized structures such as narrow filaments of dry and moist air. The bottom-left panel shows the forecast from the AI-based GEML model. Compared to GEM, large-scale moisture patterns predicted by GEML are considerably better aligned with the analysis. For example, the atmospheric river over the Pacific Ocean makes landfall over northern California, consistent with the analysis, whereas the physics-based GEM forecast incorrectly tracks the system toward British Columbia. However, the AIWP forecast appears substantially smoother and lacks realistic local-scale structure.

Finally, the bottom-right panel in Fig. 1 presents the forecast from the hybrid AIWP–NWP model. Through large-scale spectral nudging, the broad-scale circulation patterns are constrained toward the AI-based solution, while the smaller-scale structures are generated by GEM's physics-based dynamics and parameterizations. The resulting forecast therefore combines more accurate large-scale patterns than the standalone GEM model with more realistic fine-scale detail than the AI-based GEML model.

4. CONCLUSIONS

Like in many scientific disciplines, the advent of artificial intelligence is reshaping weather forecasting and challenging the status quo. However, this evolving paradigm does not imply the obsolescence of traditional physics-based NWP models. Current limitations of deterministic AIWP models, including spatial smoothing, weak representation of localized extremes, a limited set of predicted variables, and a limited ability to generalize beyond the training data, indicate that they remain far from replacing physics-based NWP models.

The hybrid AIWP-NWP framework presented here shows that combining both approaches can yield substantial gains in predictability and therefore represents a promising path forward for the foreseeable future. Advancing such hybrid systems will require continued improvements in both AI and physics-based components, as each plays a fundamental role in shaping the final predicted state.

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Advancing Engineering for a Sustainable Future (AE4SF) - 1st Int Symposium

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HOW AI IS SHAPING ENGINEERING EDUCATION: OPPORTUNITIES AND RISKS FOR THE NEXT GENERATIONS

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ABSTRACT: Artificial intelligence (AI) is rapidly reshaping engineering education through generative AI, intelligent tutoring schemes, automated response tools, and AI-enabled simulation platforms. This paper discusses the key opportunities and risks of AI adoption in engineering programs. Generally, AI can support personalized learning, multilingual assistance, increased productivity in coding and data analysis, and exposure to industry-relevant applications. Nevertheless, indiscriminate adoption may weaken foundational analytical skills, increase overdependence, complicate evaluation, and widen inequities in accessibility. The paper argues that AI should be integrated as a supervised learning tool rather than a substitute for engineering judgment. Thus, engineering curricula must combine AI literacy, ethics, transparent usage policies, and redesigned evaluations that preserve critical thinking and problem-solving capacity.

1. INTRODUCTION

Artificial intelligence (AI) is becoming a crucial force in engineering education. Generative AI, intelligent tutoring systems, AI-assisted coding environments, and simulation platforms are reshaping how students search for information, solve technical problems, prepare reports, and approach design tasks. Large language models (LLMs), including ChatGPT, Claude, Copilot, Gemini, and DeepSeek, have also become extensively available to students and educators. Thus, their influence is no longer limited to advanced computing courses; it now affects core engineering subjects such as mathematics, mechanics, materials, structures, and construction management analysis (Holmes et al. 2019; Zawacki-Richter et al. 2019).

Considering the use of AI, like any technology, may inherently have pros and cons in our education, the key question is how AI can be incorporated so that the negative effects are minimized and we can enhance the positive aspects of our engineering education (Luckin et al. 2016; UNESCO 2021). Poorly guided implementation can produce shallow learning and academic integrity concerns, while responsible adoption can enhance access, feedback, creativity, and professional readiness. Similar to earlier transitions involving computer-aided design and numerical modelling tools, AI is likely to shift the emphasis in engineering education rather than eliminate the need for foundational knowledge. Thus, students must still understand first principles, verify outputs, and exercise professional judgment, mainly because engineering decisions often affect public safety. This realization is foundational for our students. Otherwise, fully depending on AI could be disastrous for the next generation. Overall, the opportunities and risks of using AI in engineering education are captured in Figure 1.

2. OPPORTUNITIES FOR ENGINEERING EDUCATION

AI offers several opportunities to enhance teaching and learning in engineering programs. First, AI systems can support personalized learning by adapting explanations, examples, and practice problems to the requirements of individual students. This is predominantly useful in technically demanding subjects where students often require repeated explanations, step-by-step feedback, and different examples. AI tutors can offer instant support outside scheduled class hours, which may help students close knowledge gaps before they become barriers to progression (Pane et al. 2015).

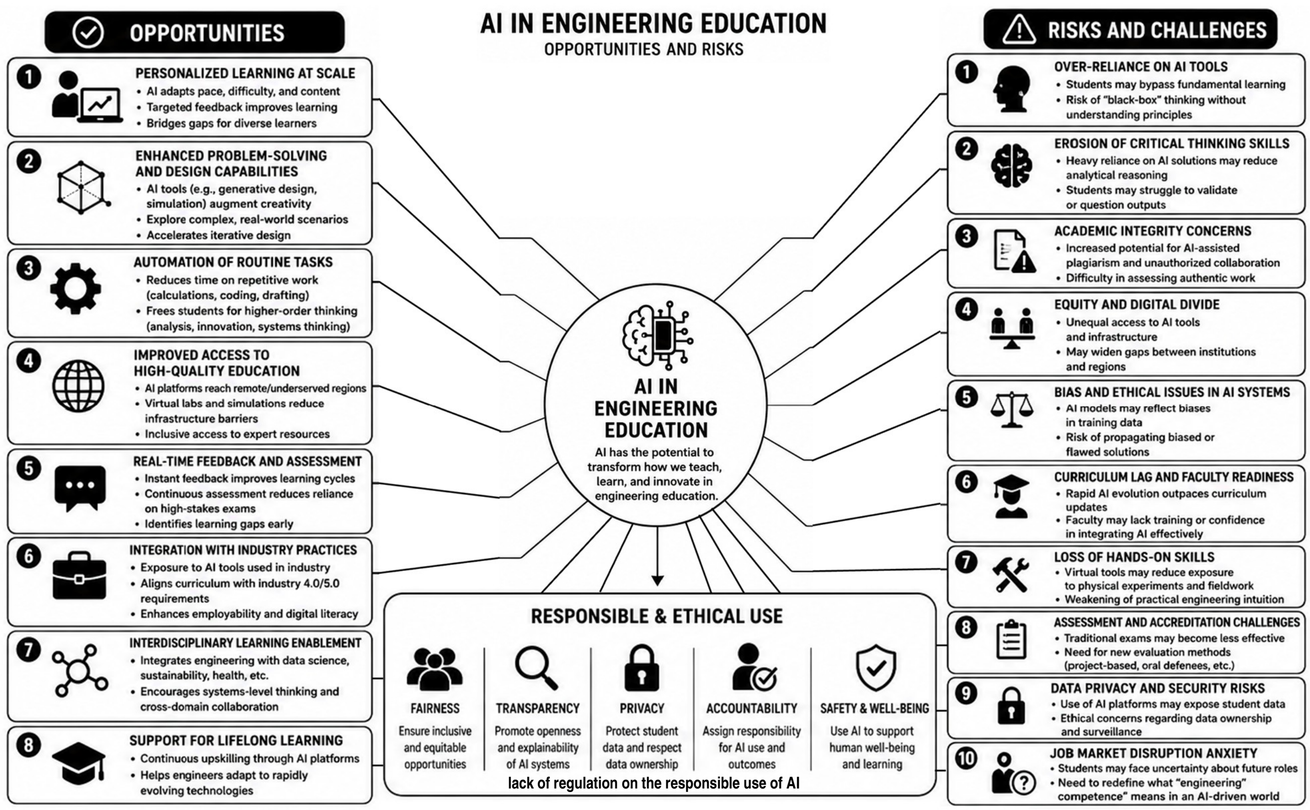

Figure 1. Overview of the major opportunities and risks of AI adoption in engineering education and the importance of responsible and ethical implementation.

Second, AI can improve accessibility and inclusive education. Students who face language barriers, learning differences, or limited access to tutoring can use AI tools for multilingual explanations, text simplification, writing support, and assisted learning. When properly supervised, AI can help broaden participation and reduce dependence on informal support networks. Still, accessibility benefits would rely on equitable availability, institutional support, and clear guidance on acceptable usage (UNESCO 2021).

Third, AI can increase productivity for both students and educators. Routine tasks such as code debugging, data cleaning, literature organization, formatting, and initial content generation can be accelerated, thereby freeing up time for conceptual understanding, design reasoning, and interpretation. Meanwhile, for educators, AI can assist with drafting examples, generating practice questions, creating rubrics, and offering appropriate feedback. These benefits are strongest when AI is used to support learning processes rather than to bypass them (Luckin et al. 2016).

Fourth, AI literacy aligns engineering education with current professional practice. Modern engineering progressively involves data-driven design, digital twins, smart infrastructure, predictive maintenance, robotics, and automated inspection systems. So, graduates who understand both the abilities and limitations of AI will be better prepared to work in interdisciplinary teams and to assess AI-supported decisions in practice. Thus, AI should be treated as a crucial component of emerging engineering competence (Lee et al. 2018).

AI is transforming engineering education by making learning more personalized, efficient, and accessible. It enables adaptive instruction tailored to individual student needs, enhances creativity and problem-solving through advanced tools, and automates routine tasks so students can focus on higher-level thinking. AI also expands access to quality education via virtual platforms and provides real-time feedback that improves learning outcomes. At the same time, it aligns education with modern industry practices, supports interdisciplinary collaboration, and promotes lifelong learning, preparing future engineers to continuously adapt in a rapidly evolving technological landscape.

3. RISKS AND CHALLENGES

Despite these opportunities, AI adoption introduces important risks. A major concern is overdependence. If students routinely rely on AI-generated solutions without understanding the underlying principles, their ability to perform independent analysis may decline, leading to “black-box” thinking. This risk is particularly serious in engineering, where errors in assumptions, units, boundary conditions, and interpretation can result in unsafe designs. AI tools can generate fluent but incorrect responses, and students may accept these AI-based outputs when they lack the confidence or knowledge to challenge them (Cotton et al. 2024; Selwyn 2019).

A related concern is loss of foundational skills. Mathematics, mechanics, programming, technical drawing, and analytical reasoning remain vital to engineering formation. Thus, AI can support these skills, but it can also mask flaws if students adopt it to complete assignments without active engagement (Kasneci et al. 2023). Heavy reliance on AI-generated solutions may reduce analytical reasoning, and students may struggle to validate or question outputs. Therefore, engineering programs must distinguish between AI usage that develops competence and that replaces learning (Bender et al. 2021). Virtual tools may reduce exposure to physical experiments and fieldwork, potentially weakening practical engineering intuition, which is critical while engineers serve in the field.

Furthermore, academic integrity is another major challenge. Generative AI complicates conventional evaluation because it can generate essays, code, calculations, and design narratives with minimal student input. This makes authorship difficult to substantiate and may reduce the reliability of assignment evaluations (Cotton et al. 2024). Besides, AI models may reflect biases in their training data, leading students to propagate biased or flawed solutions unknowingly. The use of AI platforms in education may expose sensitive student data, raising ethical concerns about privacy, data ownership, and the risk of increased surveillance. Also, unequal access to advanced AI tools may create disparities between students who can afford premium packages and those who cannot. Thus, institutions must develop transparent policies that address disclosure, fairness, privacy, and responsible usage (Wakjira et al. 2025).

4. IMPLICATIONS FOR CURRICULUM AND ASSESSMENT

Engineering education should respond to AI by restructuring curricula and assessments rather than by attempting to disregard the tool. Thus, AI literacy should be embedded across programs, including prompt formulation, verification of AI outputs, bias and uncertainty, data privacy, citation practices, and ethical responsibilities. Hence, students should learn that AI-generated responses are not authoritative unless they are independently checked using engineering principles, standards, experiments, or validated models (UNESCO 2021).

Rapid AI evolution may outpace curriculum updates, and faculty may lack the training or confidence to integrate AI effectively. Assessment strategies should also evolve. In-class problem-solving, oral examinations, live coding, design reviews, laboratory demonstrations, and project-based evaluations can support genuine understanding. Assignments should be redesigned to involve reflection, justification of assumptions, comparison with hand calculations, and transparent documentation of AI usage. Traditional assessments may become less effective; rather than asking only for final answers, educators should evaluate reasoning, verification, interpretation, and communication (Cotton et al. 2024; Kasneci et al. 2023). There is a clear need for new evaluation methods, such as project-based evaluations and oral defences.

Finally, engineering programs should highlight human skills that AI cannot replace, including creativity, judgment, teamwork, ethics, communication, and responsibility for public welfare. The future engineer will not simply be a user of AI tools, but a professional who can decide when AI is appropriate, when its outputs are unreliable, and how to integrate it responsibly into engineering workflows (Holmes et al. 2019; Luckin et al. 2016).

The AI boom has recently disrupted the job market in the tech sector. However, its impact will soon be experienced in various other sectors as well. Students may face increasing uncertainty about future roles, underscoring the need to redefine engineering competence to emphasize adaptability, critical thinking, and effective collaboration with AI systems. In engineering education, this uncertainty underscores the need to redesign curricula to focus on adaptable skills, critical thinking, and the ability to work effectively alongside AI, rather than relying solely on traditional technical competencies.

5. CONCLUSIONS

AI must not be considered a threat to our engineering education, though its careless, unstructured implementation can undermine the development of core engineering proficiency. Responsible AI use can improve personalized learning, accessibility, productivity, and industry readiness. Thus, the goal of AI implementation should be to augment, not replace, human thinking. Engineering educators should incorporate AI through clear policies, literacy training, restructured assessments, and a sustained emphasis on foundational principles and professional judgment. Future engineers must be able not only to adopt AI, but also to question, validate, and responsibly apply AI in safety-critical contexts.

Overall, engineering education requires the responsible and ethical integration of AI, ensuring fairness, transparency, privacy, and accountability in both educational practices and technological applications.

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Advancing Engineering for a Sustainable Future (AE4SF) - 1st Int Symposium

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Charting the Sky: The Pilot Career Path

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For those driven by a passion for aviation, becoming a professional pilot is both a challenging and rewarding journey. This career path requires dedication, financial commitment, and a deep sense of responsibility—but it also offers the unparalleled freedom of flight and opportunities to work in one of the world's most dynamic industries.

From Student to Certified Aviator

Mahbub Khan, an FAA Commercial Pilot and FAA Gold Seal Certified Flight Instructor, exemplifies the disciplined progression required to succeed in aviation. He holds ratings in both single- and multi-engine aircraft, including advanced type ratings in the Hawker 800 and Cessna Citation 650 business jets. His credentials reflect the structured sequence of FAA certifications every aspiring pilot must follow.

The typical civilian pilot career begins with the **Private Pilot License (PPL)**. This foundational step introduces students to the basics of aircraft operation, navigation, and safety, enabling them to fly with passengers but not for compensation. Next comes the **Instrument Rating (IR)**, which allows pilots to operate in low-visibility conditions, relying exclusively on their instruments when weather deteriorates. Building upon these skills, pilots then pursue the **Commercial Pilot License (CPL)**, qualifying them to be compensated for their flying services. Because most airline operations involve multi-engine aircraft, an additional **Multi-Engine Rating (MER)** is required. The next stage—becoming a **Certified Flight Instructor (CFI)** or **Instrument Instructor (CFII)**—is a pivotal one. Flight instructing not only sharpens teaching and communication skills but also allows pilots to accumulate crucial flight hours toward the ultimate goal: the **Airline Transport Pilot (ATP) Certificate**, the highest level of FAA certification.

Building Hours and Experience

Reaching the ATP milestone typically requires at least **1,500 hours of total flight time**, a benchmark set by the FAA to ensure thorough experience and readiness for airline operations. Most aspiring airline pilots reach this number by instructing others, flying charter or cargo missions, or undertaking other time-building roles.
The process from the first solo flight to eligibility for the ATP certificate[1] generally spans **two to three years** —with **12 to 18 months** dedicated to initial training and another **one to two years** focused on accumulating hours. Pilots can solo as young as **16 years old**, earn a PPL at **17**, and qualify for an ATP certificate at **23**, provided they hold an FAA First Class Medical Certificate, the highest standard for flight fitness.

Career Progression and Opportunities

Once ATP-certified, many pilots begin at a **regional airline**, typically as a **First Officer**. Regional airlines operate feeder services for major carriers and offer valuable real-world experience in multicrew operations, airline procedures, and complex airspace environments. After two to four years, pilots often advance to **Regional Captain**, commanding their own flights and mentoring new aviators.

The next goal is joining a **major airline**—such as Delta, United, or American—as a **First Officer**, and eventually advancing to **Captain**. At this tier, compensation increases significantly: regional airline pilots often earn between **$80,000 and $120,000 annually**, while senior captains at major airlines can exceed **$200,000 per year**, with additional benefits and schedules based on seniority[2].

Alternative Pathways: The Military Route

While most civilian pilots fund their own training, some choose the **military pathway**. Here, the government provides complete flight training in exchange for years of service. After fulfilling their military commitments, pilots must still complete the necessary FAA certifications to transition into the civilian workforce—but they do so with extensive flight and operational experience that is highly valued across the industry.

Fig. 1: Hawker 800, on the ground and at 41000 feet mean sea level

The Rewarding Journey of a Lifetime

A career in aviation is not a singular destination—it's a lifelong journey of growth, precision, and discovery. The process demands discipline and resilience but rewards pilots with an extraordinary career and a view of the world from a unique vantage point. As the aviation industry continues to expand globally, ambitious professionals like Mahbub Khan continue to inspire the next generation of aviators to set their sights skyward.

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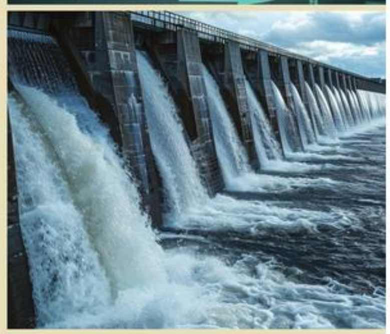

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