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CIVIL ENGINEERING RESEARCH SYMPOSIUM 2026

Book of Extended Abstracts

A collection of the extended abstracts presented at the
Civil Engineering Research Symposium 2026

Organised by

Department of Civil Engineering

University of Moratuwa

Sri Lanka

8th October 2026

Proceedings of the Civil Engineering Research Symposium 2026

8th October 2026, University of Moratuwa

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University of Moratuwa

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Civil Engineering Research Symposium 2026

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Message from the Vice Chancellor

The Civil Engineering Research Symposium has become an important annual event of the Department of Civil Engineering. I was pleased to note the Department's continued enthusiasm in organising this focused research symposium, which showcases its research achievements and highlights its significant contribution to the broader research endeavours of the University.

One of the goals that the University strives to achieve is to have a thriving and sustainable research and innovation culture in our march towards a world-class university. To this end, attempts are made to attract funding from international entities, private sector funding for research investment, international collaborations and funding from other local institutions, in addition to enhanced Senate Research Grants. This is a great opportunity for the Civil Engineering Department to contribute to the development of resilient infrastructure, disaster mitigation and innovative technologies to support rapid infrastructure development of our country.

CERS provides a valuable platform for researchers, academics, students and professionals to share knowledge, present innovative research and engage in dialogue on the evolving challenges of civil engineering. I am particularly pleased that this year, the Symposium has been expanded to include researchers from other institutions, further strengthening collaboration and knowledge exchange with a wider engineering community.

Building on this progress, I would like to see the Civil Engineering Research Symposium evolve into an international conference in the coming years, attracting researchers and academics from around the world. As a next step, I encourage the Department to work towards establishing CERS as an internationally recognised conference with peer-reviewed proceedings published through a reputed indexed publication platform. Such a development would enhance the international visibility of our research and contribute to the University's aspiration to become a globally competitive and research-intensive university.

I am also pleased that this year's Symposium pays tribute to Prof. Ananda Jayawardane, whose more than four decades of distinguished service to the University of Moratuwa, as an academic, Dean of the Faculty of Engineering and Vice Chancellor, have left an enduring legacy within our university.

While expressing my appreciation to the Head of the Department of Civil Engineering and the Organising Committee for their dedicated efforts in organising this Symposium, I also congratulate all authors on their research achievements and wish the Civil Engineering Research Symposium 2026 a great success.

Prof. K.T.M.U. Hemapala

Vice Chancellor

University of Moratuwa



Message from the Dean, Faculty of Engineering

It is my great pleasure to congratulate the Department of Civil Engineering on organising the Civil Engineering Research Symposium 2026, continuing a valued tradition that has provided an important platform for showcasing and advancing research within the Department.

Over the years, CERS has evolved into a significant forum for bringing together students, academics, researchers, alumni and industry professionals to exchange knowledge and engage with emerging developments in civil engineering. I am particularly pleased to see the Symposium expanding its scope this year to provide opportunities for undergraduate and postgraduate researchers from universities across Sri Lanka to share their work and engage with the wider academic and professional community.

Civil engineering continues to play a fundamental role in the sustainable development of our country, addressing challenges relating to infrastructure, the built environment, resilience, sustainability and the responsible use of resources. In this context, research that combines scientific rigour with practical relevance is increasingly important. A forum such as CERS provides an excellent opportunity not only to disseminate new knowledge but also to strengthen the connection between university research and the evolving needs of industry and society.

The Department of Civil Engineering has continued to strengthen its contribution to the University through excellence in undergraduate and postgraduate education, research, innovation, industry engagement and professional service. Its academic staff contribute their expertise to research and consultancy, as well as to national initiatives involving engineering, technology and policy, while students benefit from strong exposure to contemporary engineering practice and research.

I am confident that CERS 2026 will further encourage a culture of inquiry, innovation and applied research among our students and young researchers, while fostering stronger collaboration between universities, industry and the profession.

A special highlight of this year's Symposium is the Valedictory Lecture by Prof. Ananda Jayawardane, recognising more than four decades of distinguished service and his lasting contribution to the University and engineering education in Sri Lanka.

I extend my sincere appreciation to the Head of the Department of Civil Engineering, the Co-chairs and members of the Organising Committee, the editors, reviewers, academic staff and all others who have contributed to making this Symposium possible. I also congratulate all authors and presenters on their research achievements and wish the Civil Engineering Research Symposium 2026 every success.

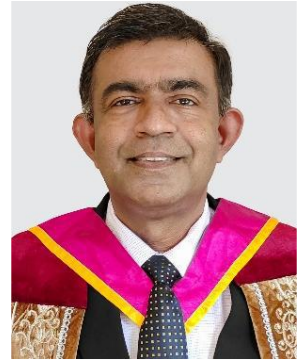
Prof. Jagath Manatunge

Dean, Faculty of Engineering
University of Moratuwa



Message from the Head of the Department

It is my great pleasure to welcome all participants to the Civil Engineering Research Symposium 2026, organised by the Department of Civil Engineering, University of Moratuwa. This year marks an important milestone in the evolution of CERS, as we welcome researchers and academics from other universities and institutions, creating a broader platform to share knowledge, present research findings, and exchange ideas on emerging challenges and opportunities in civil engineering.



This year's Symposium is particularly special as we honour Prof. Ananda Jayawardane for his outstanding service to the University of Moratuwa spanning more than four decades. Prof. Jayawardane has contributed immensely to the education of generations of civil engineers, particularly through his teaching in Construction Management, and has provided distinguished academic leadership as Dean of the Faculty of Engineering and Vice Chancellor of the University of Moratuwa. His long and dedicated service has made a lasting contribution to our Department, Faculty and University, and we are privileged to recognise his remarkable contribution at CERS 2026.

As we celebrate this legacy, we must also look towards the future. Civil engineering is undergoing rapid transformation through artificial intelligence, digitalisation, automation, advanced materials, data-driven engineering, and new approaches to sustainable and resilient infrastructure. These developments present both opportunities and challenges, requiring us to rethink how we conduct research, educate future engineers and translate knowledge into practice. At the same time, innovation must remain firmly grounded in engineering fundamentals, professional responsibility, ethics and the needs of society.

I hope CERS 2026 will encourage our students and researchers to embrace new ideas and technologies, work across disciplinary and institutional boundaries, and pursue research that is innovative, responsible and relevant to the challenges of our time.

On behalf of the Department of Civil Engineering, I extend my sincere appreciation to Prof. Ananda Jayawardane for his exceptional service and enduring contribution to the University of Moratuwa and the civil engineering profession. I wish all presenters, researchers, academics, industry professionals, and participants a stimulating and successful CERS 2026.

Prof. Udeni Nawagamuwa

Head, Department of Civil Engineering
University of Moratuwa

Preface and Acknowledgements

The Civil Engineering Research Symposium has, since its inception in 2011, provided a platform for undergraduate researchers of the University of Moratuwa to present their work to industry professionals and the academic community. CERS 2026 marks an important new phase in this journey, with the Symposium expanding its scope to include undergraduate and postgraduate research from universities across Sri Lanka. Through this broader national participation, CERS 2026 seeks to provide a platform for emerging researchers to present innovative ideas, share recent technological developments, exchange knowledge, and establish valuable connections with industry, academia, and policymakers.

This volume comprises 39 extended abstracts, each accompanied by a graphical abstract, organised under five thematic areas: Smart and Resilient Structures (11); Next-Generation Materials and Smart Construction (7); Environmental Sustainability and Climate Resilience (15); Intelligent Mobility and Transportation Systems (2); and Geotechnical, Water Resources, and Geospatial Technologies (4). Together, these contributions reflect the breadth of contemporary civil engineering research and highlight the growing emphasis on resilience, sustainability, digital technologies, advanced materials, and intelligent infrastructure.

All submissions were managed through the Microsoft Conference Management Toolkit (CMT) and subjected to a double-blind peer-review process. Authors of accepted extended abstracts subsequently submitted revised camera-ready versions incorporating the comments and recommendations of the reviewers. We sincerely thank all authors for their valuable contributions and for sharing their research through CERS 2026. We are equally grateful to the reviewers, whose careful assessments, constructive comments, and generous contribution of time and expertise have been essential in maintaining the quality of these proceedings.

Another key feature of this year's Symposium is the Live Three-Minute Thesis (3MT) Challenge, in which five presenters selected from the previously conducted round-robin session will compete live, communicating the significance and impact of their research through concise and engaging three-minute presentations.

CERS 2026 is made especially significant by the opportunity to honour Prof. Ananda Jayawardane in recognition of more than four decades of distinguished service to the University of Moratuwa. Through his teaching, academic leadership, and service as Dean of the Faculty of Engineering and Vice Chancellor of the University, he has made a lasting contribution to engineering education and to generations of civil engineers. We are deeply grateful to Prof. Jayawardane for delivering the Valedictory Lecture at this year's Symposium, making the occasion particularly memorable.

We also extend our sincere appreciation to our Chief Guest, Dr Patrick McNamara, Executive Director of the United States–Sri Lanka Fulbright Commission, for graciously accepting our invitation and joining us at the inauguration of CERS 2026.

The Symposium is held with the support and encouragement of the Vice Chancellor of the University of Moratuwa, the Dean of the Faculty of Engineering and the Head of the

Department of Civil Engineering, to whom we extend our sincere gratitude. We gratefully acknowledge the financial support provided by the Faculty of Graduate Studies (FGS), University of Moratuwa, towards the successful conduct of CERS 2026. We are grateful to the academic and non-academic staff of the Department, the student volunteers, all members of the Organising Committee, and our partners and sponsors for their generous and continued support.

On behalf of the Organising Committee

Prof. Chinthaka Mallikarachchi

Symposium Co-chair

Dr Chathura Rajapakse

Symposium Secretary

Dr Kanishka Chandrathilaka

Editor-in-Chief

Symposium Agenda

8th October 2026

Venue: Civil Engineering Auditorium, University of Moratuwa

08:00 – 08:30	Registration
08:30 – 08:35	Lighting of the Oil Lamp
08:35 – 08:40	National Anthem
08:40 – 08:50	Welcome Address by the Head, Department of Civil Engineering
08:50 – 08:55	Address by the Dean, Faculty of Engineering
08:55 – 09:00	Address by the Vice Chancellor, University of Moratuwa
09:00 – 09:30	“The Value of Values in Higher Education: Reflections from an Interdisciplinary Leader” Address by the Chief Guest Dr Patrick McNamara, Executive Director, United States–Sri Lanka Fulbright Commission
09:30 – 10:00	“Need Seed matching for industry competitiveness” Valedictory Lecture by Prof. Ananda Jayawardane Senior Professor, Department of Civil Engineering
10:00 – 10:15	Recognition of Student Excellence: Publications in Q1/Q2 Journals
10:15 – 10:30	Acknowledgement of Partners
10:30 – 11:00	Morning Tea
11:00 – 12:30	Technical Presentation: Morning Session
12:30 – 13:30	Lunch
13:30 – 15:15	Technical Presentation: Afternoon Session
15:15 – 15:45	Three-Minute Thesis Challenge: Live Final
15:45 – 15:50	Concluding Remarks and Vote of Thanks
15:50 – 16:15	Afternoon Tea

Chief Guest



Dr Patrick McNamara

Executive Director,
United States–Sri Lanka Fulbright Commission

Patrick McNamara, PhD, serves as Executive Director of the United States–Sri Lanka Fulbright Commission. He has worked with universities, governments, corporations, nonprofits and foundations for over 35 years. Before joining Fulbright Sri Lanka, he was at the University of Nebraska at Omaha (UNO), where he taught conflict resolution, sustainable development and social entrepreneurship. At UNO, he served as Senior International Officer, Director of the International Studies major and minor, Director of the Sustained Dialogue Initiative and Director of the Omaha World Affairs Council.

Dr McNamara earned a PhD from the School of Public Administration at UNO, an MSc in Conflict Analysis and Resolution from George Mason University, and a BA in Religion from Swarthmore College, where he studied comparative religions and ethics.

His address is titled “The Value of Values in Higher Education: Reflections from an Interdisciplinary Leader”.

Valedictory Lecture: “Need Seed matching for industry competitiveness”



Prof. Ananda Jayawardane

Professor, Department of Civil Engineering, University of Moratuwa

Professor Ananda Jayawardane is a distinguished academic, visionary leader and pioneering administrator who has shaped the University of Moratuwa through a career of more than four decades. His contributions span teaching, research, institutional governance and industry collaboration, and he has served the University as Head of two departments, Dean of the Faculty of Engineering and Vice Chancellor.

He graduated with First Class Honours in Civil Engineering from the University of Moratuwa in 1983, and obtained his MSc in Construction (1986) and PhD in Construction Management (1990) from Loughborough University of Technology, UK, followed by training in Technology Management at the Asian Institute of Technology, Thailand. He joined the Department of Civil Engineering as an Assistant Lecturer in 1984, and was promoted to Senior Lecturer in 1990, Associate Professor in 1998, Professor in 2001 and Senior Professor in 2009.

He was the founding Head of the Department of Management of Technology (1998 to 2002), where he launched the University’s first MBA programme, and Head of the Department of Civil Engineering (2002 to 2004). In the latter role he introduced student mentoring and industry-based leadership programmes, which have since become standard practice across the University, together with the 5S productivity programme and peer observation of teaching, well before formal quality assurance systems were in place. He was the lead architect of the University’s first participatory Corporate Plan (2001 to 2006), and subsequently led its strategic planning four times, covering the period 2007 to 2021.

As Dean of the Faculty of Engineering (2004 to 2010), he increased student intake by 35% while maintaining academic quality, established the Department of Transport and Logistics Management, secured the Faculty’s first endowed professorship, institutionalised departmental and faculty industry consultative boards, and ensured that the engineering degree programmes obtained Washington Accord accreditation.

As Vice Chancellor (2011 to 2017), he led a systemic transformation of the University. The Faculty of Graduate Studies and the Faculty of Business were established, the latter introducing

the Bachelor of Business Science, a pioneering degree in the national university system, and the foundation was laid for the Faculty of Medicine. He established the Enterprise Innovation and Entrepreneurship Incubator and seven focused research centres, and oversaw a major expansion of the University's land, buildings and infrastructure.

His service to the nation includes membership of the University Grants Commission (2020 to 2024), chairmanship of the Committee of Vice-Chancellors and Directors (2014), and membership of the councils of the National Institute of Education and the National Education Commission. He was President of the Institution of Engineers, Sri Lanka (2010 to 2011), and has served as Chairman of the Commercial Bank of Ceylon PLC and as a director of organisations including the Construction Industry Development Authority, HNB Life PLC, Sierra Cables PLC, the State Engineering Corporation and the Bank of Ceylon.

He is a Chartered Engineer, an International Professional Engineer, and a Fellow of the Institution of Engineers, Sri Lanka, the Institute of Project Managers, Sri Lanka, and the National Academy of Sciences of Sri Lanka. He is also a Founder Member of the Society of Structural Engineers, Sri Lanka, a Life Member of the Sri Lanka Association for the Advancement of Science and a Graduate Member of the Sri Lanka Institute of Directors. His awards include the IESL Award for Eminence in Engineering (2018), the highest lifetime award of the Institution for the practice of engineering, several awards for outstanding contribution to education from the World Education Congress and CMO Asia (2016 to 2018), and the National Achiever's Award for Engineering from the Lions Clubs International (2013).

Three-Minute Thesis (3MT) Challenge: Finalists



J.H.M.Y.U. Jayapathma

Effect of Particle-Size Distribution on the Resilient Modulus of Tunnel Muck for Pavement Applications



K.I. Keshani

T-Shaped Deep Mixing Method for Soft Ground Improvement



P.H.T. Punchihewa

Seismic Vulnerability Assessment of Residential Buildings in Sri Lanka



V.O. Ratnayake

Listening to a Heated Conversation



L.A.D.T. Senaratne

Buckling Behaviour of Cold-Formed Steel Z-Sections under Axial Compression and Bi-Axial Bending

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NUMERICAL EVALUATION OF SHEAR PERFORMANCE IN COLD-FORMED STAINLESS STEEL SUPACEE SECTION WITH WEB OPENINGS

R. Ajithmilan^{1*}, E.R.S.B. Miranda¹, M.F.M. Ishqy¹, Keerthan Poologanathan²

¹ Department of Civil Engineering, South Eastern University of Sri Lanka

² School of Engineering, Physics and Mathematics, Northumbria University, UK

**Corresponding author: rajanajithmilan@gmail.com*

Abstract

Cold-formed stainless-steel (CFSS) members offer corrosion resistance and lightweight structural efficiency, making them suitable for a range of structural applications. Web openings are commonly introduced into CFSS SupaCee sections to accommodate building services and minimise storey height; however, they reduce the effective web area and consequently the shear capacity. Research on the shear strength reduction caused by circular web openings in CFSS SupaCee sections remains limited. This study presents a numerical investigation of the shear behaviour and capacity of cold-formed duplex stainless-steel (grade 1.4462) SupaCee sections containing unreinforced circular web openings. A parametric study comprising 120 finite element models was undertaken following validation against existing experimental shear test data to investigate the effect of circular web openings on shear capacity. The numerical results were used to develop a third-order polynomial equation for predicting the shear reduction factor. The proposed equation showed close agreement with the finite element results, with a mean FE-to-predicted ratio of 1.0010 and a coefficient of variation of 0.0640.

Keywords: Duplex stainless steel, Thin-walled member, Reduction factor, Circular web opening

1. Introduction

Cold-formed stainless-steel (CFSS) sections are increasingly utilised in structural applications due to their durability, corrosion resistance, and reduced maintenance requirements. Stainless steel exhibits a nonlinear stress–strain response with gradual yielding and pronounced strain hardening, which differs from the elastic–perfectly plastic behaviour commonly assumed for carbon steel [1]. Previous numerical and experimental studies have shown that material nonlinearity influences the buckling behaviour and ultimate strength of cold-formed stainless-steel members, particularly those subjected to shear [2], [3].

Web openings are commonly introduced into cold-formed sections to accommodate building services and minimise storey height; however, they can reduce the shear resistance of the member [4]. Previous studies have investigated the shear behaviour of carbon-steel SupaCee sections [5] and cold-formed stainless-steel lipped channel sections with web openings [4]. However, the shear behaviour of duplex stainless-steel SupaCee sections with circular web openings remains insufficiently investigated. Therefore, this study investigates the shear behaviour of cold-formed duplex stainless-steel (grade 1.4462) SupaCee sections containing unreinforced circular web openings. Finite element (FE) models were developed and validated against existing experimental shear test data, followed by a parametric study comprising 120 FE models. The numerical results were used to evaluate the effect of web openings on shear capacity and develop a polynomial equation for predicting the shear reduction factor.

2. Methodology

Pham and Hancock tested SupaCee sections with depths of 150 mm and 200 mm and thicknesses of 1.2 mm, 1.5 mm, and 2.4 mm [5]. Six test results were selected for FE validation. The corresponding models were developed in ABAQUS using S4R shell elements and incorporating material and geometric nonlinearities. The nonlinear stress–strain behaviour of stainless steel was represented using the Ramberg–Osgood formulation of Arrayago et al. [1], while cold-forming-induced strength enhancement in the corner regions was incorporated using the corner-enhancement relationships adopted from Ishqy et al. [4]. The experimental support and loading conditions were replicated, and the nonlinear response was obtained using the Static Riks method to capture post-buckling behaviour. Mesh sensitivity was assessed by refining the mesh in critical regions, and the selected mesh was used for the subsequent parametric analyses. Geometric imperfections were introduced using the Mode 2 eigenmode obtained from linear buckling analysis. Two imperfection amplitudes, 0.15t and 0.64t, where t is the web thickness, were considered during validation. Both amplitudes provided good agreement with the experimental results, giving a mean Test/FEA ratio of 0.98 and a coefficient of variation (COV) of 0.04, as summarised in Table 1. The corresponding experimental and FE load–displacement responses are compared in Figure 1. The 0.64t amplitude was subsequently adopted for the parametric FE models. Residual stresses arising from cold forming were not explicitly modelled, with their effects implicitly considered through the adopted material modelling and geometric imperfections.

Table 1: Comparison of experimental and FE shear capacities.

No	SupaCee Section	Test Shear Capacity (kN)	Test/FEA	
			Mode 2 0.15t	Mode 2 0.64t
1	SC15012	168.72	0.99	0.97
2	SC15015	222.24	0.96	0.96
3	SC15024	391.44	1.01	1.02
4	SC20012	186.01	0.94	0.93
5	SC20015	248.13	0.94	0.97
6	SC20024	495.81	1.03	1.03
		Mean	0.98	0.98
		COV	0.04	0.04

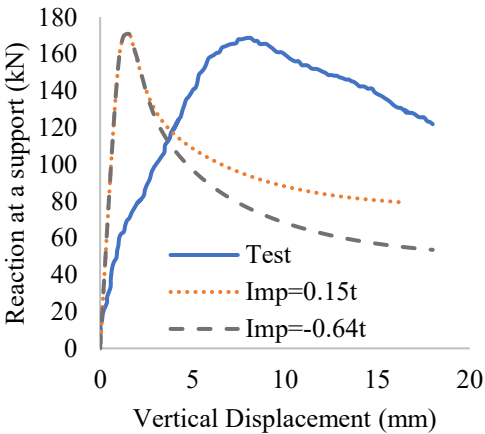


Figure 1: Comparison of experimental and FE load–displacement responses.

Following validation, a parametric study was conducted on duplex stainless steel EN 1.4462 SupaCee sections to investigate the influence of circular web openings on shear capacity. The same FE modelling methodology was retained, with the material properties in ABAQUS modified for EN 1.4462. Three section depths (100, 150, and 200 mm), four thicknesses (1.2, 1.5, 2.0, and 3.0 mm), and opening ratios ranging from 0 to 0.85 were investigated, with an opening-to-web-depth aspect ratio of 1.0. A total of 120 FE models were analysed. The resulting numerical database was used to quantify the reduction in shear capacity with increasing opening size and to develop a regression-based shear-capacity reduction relationship for duplex stainless-steel SupaCee sections.

3. Results

The validated FE model was used to investigate the shear behaviour of duplex stainless steel (EN 1.4462) SupaCee sections with circular web openings. The FE results showed a progressive reduction in shear capacity with increasing web opening ratio. Three shear reduction formulations, comprising one linear and two polynomial equations, were evaluated using the FE database. The third-order polynomial equation resulted in the lowest coefficient of variation (COV) of 0.0640, with a mean FE-to-predicted ratio of 1.0010, and was therefore selected to represent the shear-capacity reduction of duplex stainless-steel SupaCee sections. The proposed equation and its comparison with the FE results are presented in Figure 2.

$$q_s = 1.6992\left(\frac{d_{wh}}{d_1}\right)^3 - 2.3694\left(\frac{d_{wh}}{d_1}\right)^2 - 0.0703\left(\frac{d_{wh}}{d_1}\right) + 1.0075$$

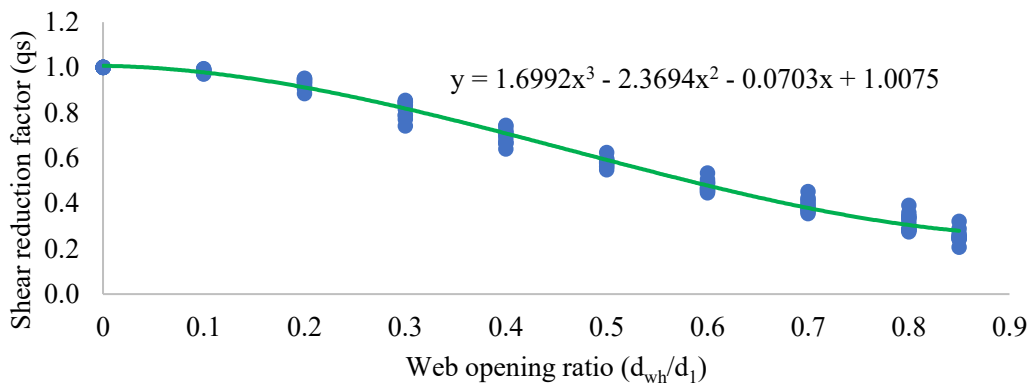


Figure 2: FE results and proposed third-order polynomial equation.

References

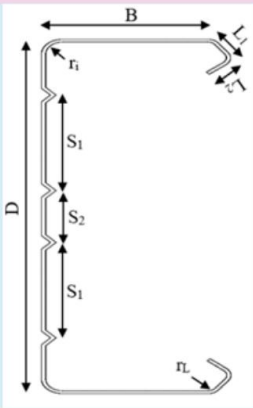
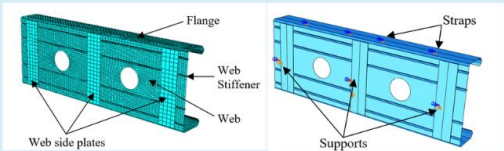
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Cold-Formed Stainless Steel SupaCee Sections with Circular Web Openings

This research investigates the shear behaviour of cold-formed stainless steel SupaCee sections with circular web openings. Two stainless steel grades were examined: austenitic (1.4301) and duplex (1.4462). A total of 240 finite element (FE) models were developed, validated against experimental data, and used in a parametric study to propose new shear reduction factor equations for design practice.

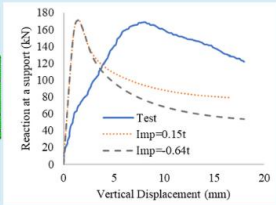
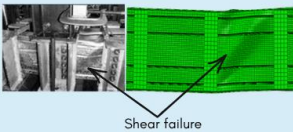
SupaCee Cross-Section Geometry

The SupaCee section features a lipped channel profile with a circular web opening. Key geometric parameters include d_{wh} (opening diameter) and d_1 (clear web depth). The opening ratio d_{wh}/d_1 governs shear capacity reduction and is the primary variable in the parametric study.



FEA Validation Results

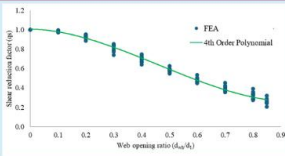
FE models were validated against experimental test results. The mean Test/FEA ratio was 0.98 with a coefficient of variation (COV) of 0.04, confirming excellent agreement between numerical predictions and physical tests. This high accuracy validates the FE modelling methodology for the parametric study.



Section	Thickness(mm)	Steel type	d_{wh}/d_1	Number of models
SC100	1.2, 1.5, 2.0, 3.0	EN 1.4301, EN 1.4462	0.00, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.85	80
SC150	1.2, 1.5, 2.0, 3.0	EN 1.4301, EN 1.4462	0.00, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.85	80
SC200	1.2, 1.5, 2.0, 3.0	EN 1.4301, EN 1.4462	0.00, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.85	80
Total				240

FE Modelling

A total of 240 finite element models were developed in ABAQUS using shell elements (S4R). Models incorporated geometric and material nonlinearities, initial geometric imperfections, and residual stresses. The parametric study varied d_{wh}/d_1 ratios, section sizes, and steel grades systematically.



Proposed Reduction Factor Equations

$$\phi_v = -3.4278\left(\frac{d_{wh}}{d_1}\right)^4 + 7.4843\left(\frac{d_{wh}}{d_1}\right)^3 - 5.4085\left(\frac{d_{wh}}{d_1}\right)^2 + 0.4345\left(\frac{d_{wh}}{d_1}\right) + 0.9973$$

ANALYSIS AND PREDICTION OF TRANSITION LENGTH IN CIRCULAR THIN SHELL DEPLOYABLE BOOMS

R.G.P.M. Ranatunga¹, H.M.Y.C. Mallikarachchi^{1*}

¹ University of Moratuwa, Katubedda, Sri Lanka

**Corresponding author: yasithcm@uom.lk*

Abstract

Coilable thin shell booms are components of deployable space structures, where the transition from a locally flattened state to the recovered circular cross section governs the extent of geometric disturbance along the boom. This study investigates the transition length of circular thin shell booms using finite element modelling, experimental validation and analytical prediction. Numerical models were developed in Abaqus to examine the influence of boom length, radius and wall thickness. Experimental tests using UPVC tubes showed good agreement with the predicted cross-sectional deformation profiles. The results indicate that transition length becomes independent of boom length once sufficient length is available for complete recovery, while increasing radius increases transition length and increasing wall thickness reduces it. A reduced analytical model based on ovalisation, membrane stretching and circumferential bending was developed and reproduced the observed geometric trends. The proposed model provides a basis for estimating transition length in circular deployable booms.

Keywords: Thin shells, Deployable booms, Coiling, Transition region, Ovalisation

1. Introduction

Coilable thin-shell booms are widely used in deployable space structures because of their compact stowage and ability to recover their deployed shape [1]. During deployment, a transition region forms between the flattened and recovered cross-sections, where significant geometric and curvature changes occur. Although transition behaviour has been widely studied for open-section tape springs, closed-section configurations remain less explored. Practical deployable booms are commonly manufactured from orthotropic composite laminates [1], whereas the present analytical model and UPVC validation are isotropic. This study investigates transition length using finite element modelling, experiments and analytical prediction, considering the effects of boom length, radius and wall thickness.

2. Numerical and Experimental Investigation

Circular cylindrical booms were modelled using Abaqus with one end locally flattened. The variation of the cross section along the boom was quantified using the ratio between the two principal axes, where a ratio of unity represents the original circular cross section. An initial study considered 46 numerical models with a radius of 20 mm and boom lengths ranging from 200 mm to 4400 mm. The results showed that the cross section initially recovered towards the circular configuration, passed through the original shape and then gradually approached the undeformed state. For sufficiently long booms, the transition profile and the distance required for recovery remained almost unchanged with further increases in boom length.

Experimental validation was carried out using UPVC tubes with a diameter of 63 mm, an average thickness of 1.075 mm, an elastic modulus of 3000 MPa and a Poisson's ratio of 0.38. Specimen lengths of 260, 450, 650, 950 and 1450 mm were tested. One end of each tube was flattened using wedge clamps, while longer specimens were supported at the free end to minimise deformation due to self-weight. The measured cross-sectional deformation profiles showed good agreement with the numerical results as shown in Figure 1.

The influence of boom length showed that shorter specimens deviate near the free end because they do not contain sufficient length for complete recovery. In longer booms, the deformation profiles were almost identical, indicating that transition length is primarily governed by local shell geometry rather than total boom length.

Boom diameter had a strong effect on transition length. Models with diameters from 32 mm to 110 mm showed that the transition length increased as the diameter increased. Smaller-diameter booms experienced larger changes in transverse curvature and steeper variations in longitudinal slope, allowing the cross section to recover over a shorter axial distance.

Wall thickness showed the opposite behaviour. For a 63 mm diameter boom, increasing the thickness from 1 mm to 5 mm reduced the distance required for cross-sectional recovery. For thicker shells, shear deformation also became increasingly significant near the flattened region, causing the deformation to become more localised.

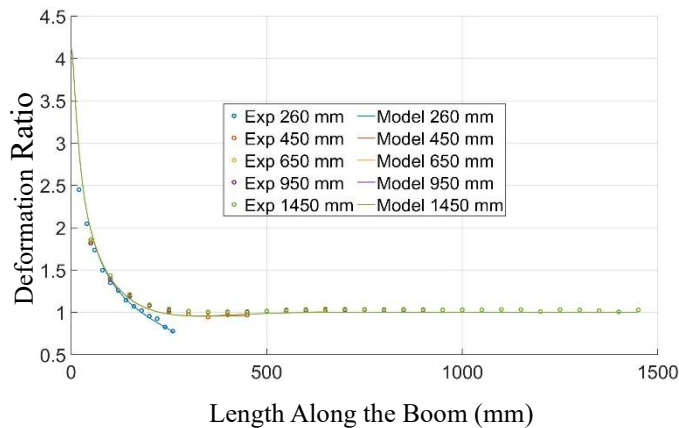


Figure 1: Comparison between experimental and numerical deformation profiles.

3. Analytical Model

A reduced analytical model was developed for a circular cylindrical shell with radius R , thickness t , Young's modulus E and Poisson's ratio ν . The transition was assumed to be dominated by the $n = 2$ ovalisation mode, with radial displacement expressed as

$$w(x, \theta) = W(x) \cos(2\theta) \text{ ----(1)}$$

The shell was assumed to be thin and isotropic, with negligible circumferential strain and in-plane shear strain. Only axial membrane stretching and circumferential bending energies were retained [2]. Minimisation of the total strain energy using the Euler–Lagrange equation gives

$$W'''' + \frac{12t^2}{R^6} W = 0 \text{ -----(2)}$$

The bounded solution for the ovalisation amplitude is

$$W(x) = A_2 e^{-qx} [\cos(qx) + \sin(qx)] \text{ -----(3)}$$

where, $q = 3^{1/4} \frac{\sqrt{t}}{R^{3/2}}$ and A_2 is maximum radial displacement at clamped end

This predicts an oscillatory recovery with an exponentially decaying amplitude, consistent with the numerical response.

The resulting transition length is

$$L^{\text{transition}} = \frac{(3 + \ln A_2) R^{3/2}}{3^{1/4} \sqrt{t}} \text{ ----- (4)}$$

This predicts longer transition lengths for larger radii and shorter lengths for greater thicknesses. The analytical model overpredicts the FEM results, with maximum discrepancies of 32.4% for varying radius and 38.1% for varying thickness. The differences mainly arise because only the $n = 2$ ovalisation mode is represented, whereas the strongly flattened region can contain higher circumferential modes captured by FEM. In addition, axial and twisting curvature energies are neglected; although small in the outer transition region, they may influence the response near the imposed flattening. Despite these simplifications, the model captures the dominant geometric trends observed numerically over the range of parameters

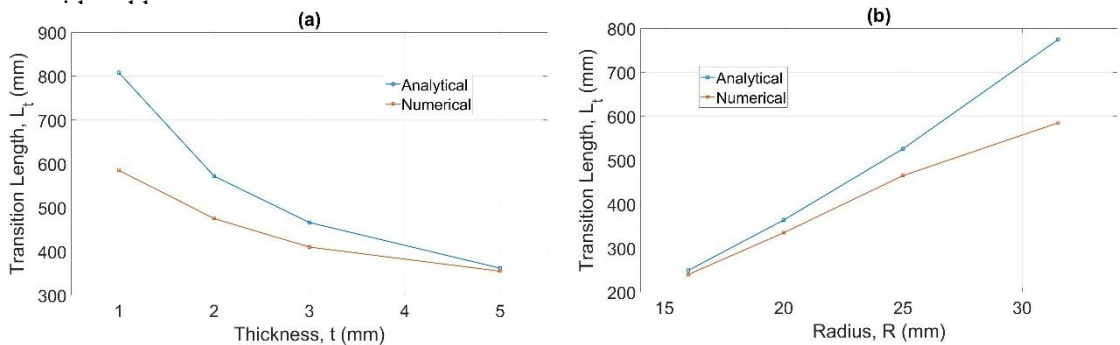


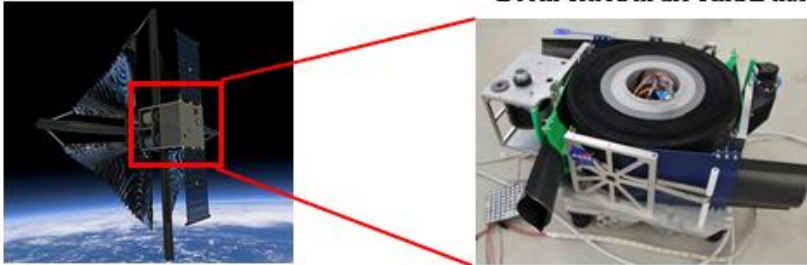
Figure 2: Comparison of analytical and numerical transition lengths: (a) varying thickness; (b) varying radius.

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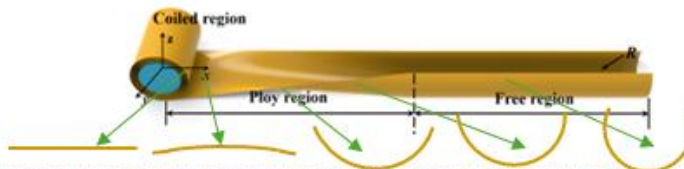
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ANALYSIS AND PREDICTION OF TRANSITION LENGTH IN CIRCULAR THIN SHELL DEPLOYABLE BOOMS

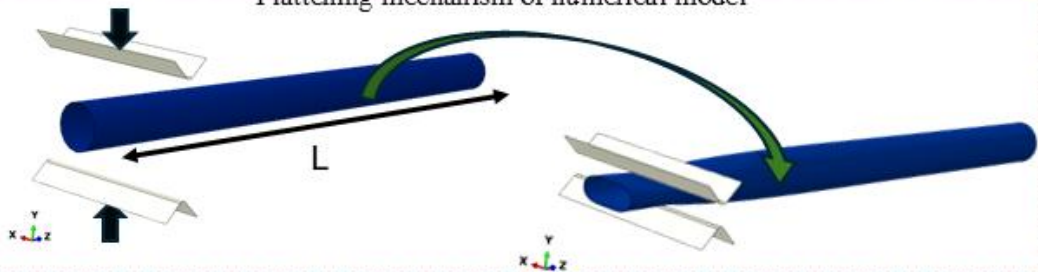
Deployment of space structures using coiled deployable booms
Boom coiled in the central hub



Transition region between coiled and deployed region



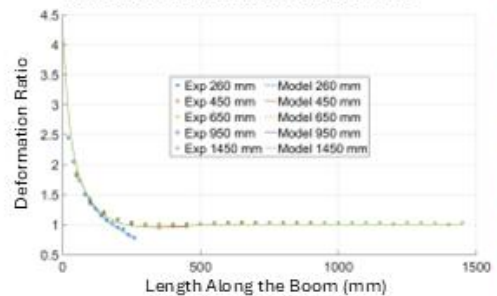
Flattening mechanism of numerical model



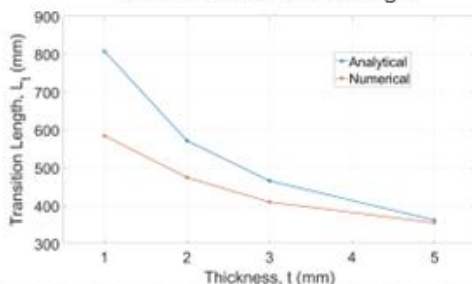
Experimental setup



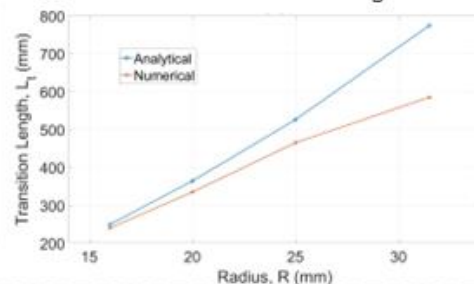
Validation of numerical model



Comparison between analytical and numerical model
thickness vs transition length



radius vs transition length



MULTILEVEL RELIABILITY ASSESSMENT OF MASONRY INFILL STRUT MODELS UNDER SEISMIC LOADING

Siyavur Raheem^{1*}, Julian Thamboo², Chinthaka Mallikarachi¹, Kushan Wijesundara³, Priyan Dias⁴

¹ Department of Civil Engineering, University of Moratuwa

² Department of Civil Engineering, South Eastern University of Sri Lanka

³ Department of Civil Engineering, University of Peradeniya

⁴ Sri Lanka Institute of Information Technology

**Corresponding author: raheemmacs.23@uom.lk*

Abstract

Reinforced concrete frames infilled with masonry walls (RC-IMW) are a commonly used configuration for low-to-medium-rise buildings in Sri Lanka. To analyse their seismic performance, they are represented as equivalent infill strut models in the structural analysis. Several masonry infill strut models have been proposed in the past, yet their reliability is not well assessed. This study evaluates the reliability of five recently developed strut models using the first-order reliability method. An experimental database comprising single-bay single-storey tests and multi-storey tests was utilised. Non-linear numerical models of infilled frames were developed, and their in-plane load-displacement and time-history responses were compared with the experimental results using mean error and root mean square error. The results showed that the predicted reliability indices of the models vary between 1.03 and 4.13. Subsequently, the weighted sum method, assigning equal weight to all the considered scenarios, was employed to propose the most reliable model.

Keywords: First-order reliability method, In-plane, Masonry infills, Reinforced concrete, Seismic

1. Introduction

Reinforced concrete frames infilled with masonry (RC-IMW) buildings are common in low-to-medium-rise building construction in Sri Lanka. Although IMWs are treated as non-structural elements, they strongly interact with surrounding frames under seismic loading. Recent post-earthquake damage surveys have shown that omitting this interaction in the structural analysis led to unintended shear failures and to stiffness and torsional irregularities [1]. RC-IMWs are commonly represented in structural analysis through a macro-modelling approach, where the IMWs are idealised as masonry struts [2]. Several masonry strut models have been proposed in the past, but they are typically calibrated only against single-bay single-storey test data. Furthermore, the current literature has focused on the best predictive model, while the dispersion associated with those models has been unexamined. Their reliability, particularly for multi-storey frames, has not been verified.

In this study, the reliability of five recent infill masonry strut models, namely Liberatore et al. [3], De Risi et al. [4], Mucedero et al. [5], Huang et al. [6], and Di Trapani [7] has been evaluated. A database comprising single-bay single-storey tests and multi-storey tests was developed. Non-linear numerical models were developed in OpenSees [8] using the test database and considering five masonry strut models. The reliability indices were computed by predicting the response and employing the first-order reliability method (FORM) [9]. Response prediction and reliability index computation were carried out for yield, peak and ultimate cases for the single-bay single-storey tests and the base shear and storey drift predictions of the multi-

storey RC-IMW shake table tests. Subsequently, the model of Liberatore et al. [3] was identified as the most reliable using the weighted sum method.

2. Methodology

A database comprising 150 single-storey single-bay and three multi-storey tests was developed. Replicas of these experiments were modelled in OpenSees [8] using five recent infill masonry strut models. Numerical predictions were made and compared with experimental outcomes, determining the mean model error and standard deviation for yield, peak and ultimate force and displacement for single-storey single-bay test, as well as base shear and top storey displacement for multi-storey cases. Then the reliability indices were computed by employing the FORM [9]. The strut models were ranked (in parentheses) based on the reliability index for each case. A weight was assigned for each ranking. For 1st, 2nd, 3rd, 4th and 5th ranks 1, 0.8, 0.6, 0.4 and 0.2 were assigned, respectively. Every case was considered equally important while assigning weight. Finally, the most reliable model was identified using the sum of these weights, shown in Table 1.

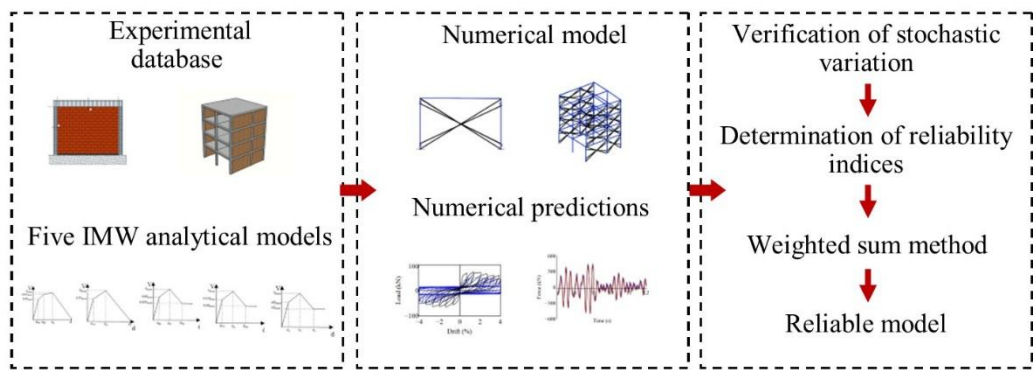


Figure 1: Methodology of the study.

3. Results and Discussion

It can be noted from Table 1 that no single model outperformed the others across all cases. Therefore, the selection of models should be guided by the specific requirements of the seismic assessment. A model offering a high reliability index for load-based cases may not be as reliable for drift-based cases, and vice versa. Overall, Liberatore et al. [3] provides more reliable predictions in most cases compared to the other models.

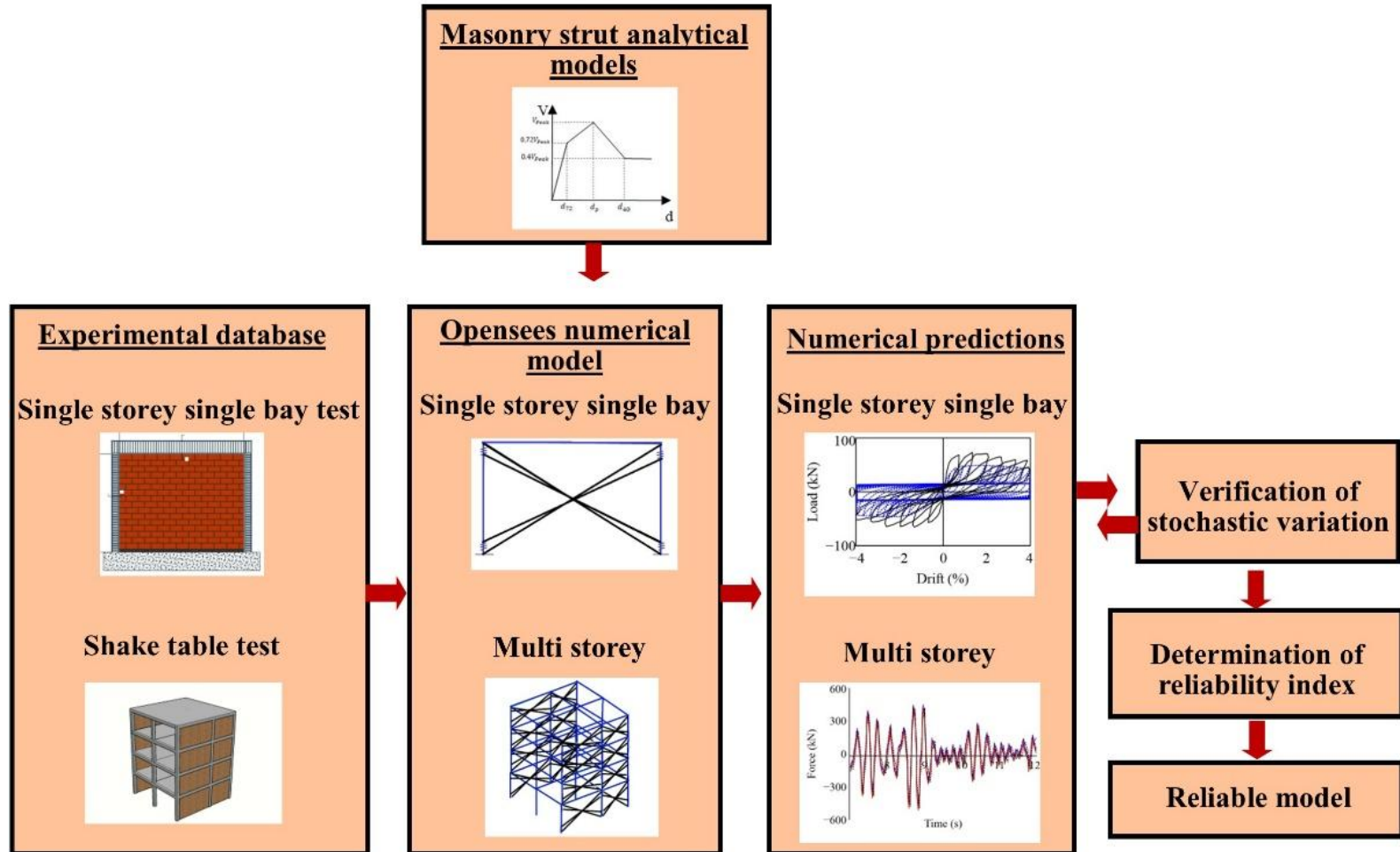
Table 1: Results of the study.

Parameters			Liberatore et al. [3]	De Risi et al. [4]	Mucedero et al. [5]	Huang et al. [6]	Di Trapani [7]
Single-storey single-bay frame	Yield	Drift	2.33 (5)	2.70 (2)	2.43 (4)	2.87 (1)	2.54 (3)
		Score	0.2	0.8	0.4	1	0.6
		Load	2.36 (3)	2.73 (1)	2.68 (2)	2.05 (4)	1.71 (5)
		Score	0.6	1	0.8	0.4	0.2
	Peak	Drift	3.67 (3)	3.69 (2)	3.50 (4)	2.89 (5)	3.76 (1)
		Score	0.6	0.8	0.4	0.2	1
		Load	1.65 (3)	1.83 (1)	1.82 (2)	1.53 (4)	1.29 (5)
		Score	0.6	1	0.8	0.4	0.2

Multi-storey frame	Ultimate	Drift	3.54 (1)	3.33 (2)	3.17 (4)	3.29 (3)	2.33 (5)
		Score	1	0.8	0.4	0.6	0.2
		Load	3.05 (1)	2.70 (2)	2.68 (3)	2.06 (4)	1.71 (5)
		Score	1	0.8	0.4	0.6	1
	Study 1	Storey drift	2.85 (3)	2.86 (2)	2.28 (5)	2.62 (4)	3.14 (1)
		Score	0.6	0.8	0.2	0.4	1
		Base shear	1.78 (2)	1.77 (3)	1.99 (1)	1.11 (4)	1.05 (5)
		Score	0.8	0.6	1	0.4	0.2
	Study 2	Storey drift	3.68 (1)	1.11 (4)	1.19 (3)	1.61 (2)	1.10 (5)
		Score	1	0.4	0.6	0.8	0.2
		Base shear	2.29 (3)	1.03 (5)	2.49 (1)	2.28 (4)	2.57 (2)
		Score	0.6	0.2	1	0.4	0.8
	Study 3	Storey drift	3.81 (5)	4.12 (3)	4.12 (3)	4.13 (1)	4.12 (2)
		Score	0.2	0.6	0.6	1	0.8
		Base shear	3.90 (1)	1.08 (4)	1.09 (3)	1.08 (4)	1.11 (2)
		Score	1	0.4	0.6	0.4	0.8
	Weighted sum		8.2	7.2	7.2	6.8	7.4

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COMPARISON OF ANALYTICAL AND NUMERICAL MODELS FOR PREDICTING THE CAPACITY OF DAPPED-END CONNECTIONS

S.G.M.N.D. Kumarasinghe¹, H.M.S.T. Herath¹, R.M.C.M. Rajapakse^{1*}

¹ Department of Civil Engineering, Faculty of Engineering, University of Moratuwa, Moratuwa, Sri Lanka

**Corresponding author: chathura.rajapakse@uom.lk*

Abstract

Reinforced concrete (RC) dapped-end connections are widely used in precast concrete structures; however, their abrupt geometric discontinuity results in complex stress distributions and brittle failure mechanisms, making the accurate prediction of their load-carrying capacity a significant engineering challenge. This study compares the predictive performance of representative analytical and numerical models for estimating the ultimate capacity of RC dapped-end connections. Three analytical models, namely the classical Strut-and-Tie Model (STM) proposed by Schlaich and Schäfer, the Precast/Prestressed Concrete Institute (PCI) design method, and the Kinematics-Based Model (KBM), were evaluated using the experimental results of eight large-scale, orthogonally reinforced dapped-end specimens from a previous experimental programme. In addition, a nonlinear finite element model was developed in VecTor2 using the Disturbed Stress Field Model (DSFM) and validated against the experimental data. The predicted capacities obtained from each model were compared with the measured ultimate loads. The results showed that the KBM provided the most accurate analytical predictions, while the VecTor2 model also demonstrated excellent agreement with the experimental results. The findings highlight the effectiveness of mechanics-based analytical and nonlinear numerical models for the reliable assessment of reinforced concrete dapped-end connections.

Keywords: Dapped-end connections, Strut-and-tie model, Kinematics-based model, Nonlinear finite element analysis, VecTor2

1. Introduction

Reinforced concrete (RC) dapped-end connections, also known as half-joints or Gerber joints, are widely used in precast concrete structures due to their structural efficiency and reduced construction depth. However, the geometric discontinuity at the re-entrant corner creates a disturbed region (D-region) with highly concentrated stresses, making the accurate prediction of their load-carrying capacity a challenging task. Several analytical approaches, including strut-and-tie models, empirical and semi-empirical methods, and kinematics-based models, have been developed to estimate their ultimate capacity, while nonlinear finite element analysis (NLFEA) has become an effective numerical tool for simulating their structural behaviour [1], [2], [5]. This study evaluates the predictive accuracy of representative analytical models and a validated VecTor2 finite element model by comparing their predictions with the experimental results of eight orthogonally reinforced dapped-end specimens tested by Rajapakse et al. [3].

2. Analytical and Numerical Models

Three representative analytical models were used to evaluate the capacity of reinforced concrete dapped-end connections: the classical Strut-and-Tie Model (STM) proposed by Schlaich and Schäfer [5], the Precast/Prestressed Concrete Institute (PCI) [1] design method, and the Kinematics-Based Model (KBM) proposed by Rajapakse et al. [2]. The STM and PCI

approaches estimate the ultimate capacity based on force equilibrium and load-transfer mechanisms, whereas the KBM predicts the capacity using the kinematics of the critical re-entrant corner crack. In addition, a nonlinear finite element model was developed in VecTor2 based on the Disturbed Stress Field Model (DSFM) to replicate the experimental specimens tested by Rajapakse et al. [3]. The model incorporated the specimen geometry, reinforcement layout, boundary conditions, and loading configuration, with concrete modelled using the Popovics constitutive model and the Vecchio (1992) compression softening relationship. The analytical and numerical predictions were validated against the experimental results of eight orthogonally reinforced dapped-end specimens, and the developed finite element model provided a reliable framework for predicting the structural behaviour and ultimate capacity of RC dapped-end connections, as shown in Figure 1.

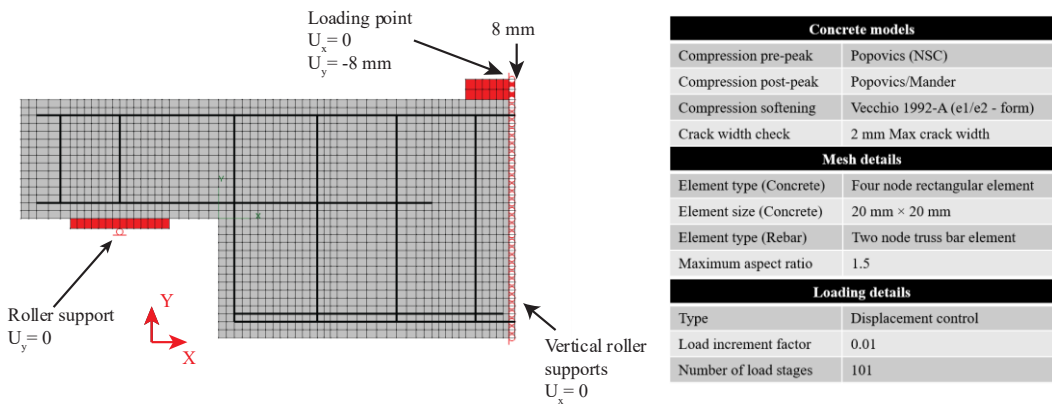


Figure 1: Finite element model developed in VecTor2 showing the mesh, boundary conditions, loading configuration, and modelling parameters.

3. Results and Discussion

Figure 2 compares the experimental peak capacities with the predictions obtained from the analytical and numerical models. The Kinematics-Based Model (KBM) [2] showed the closest agreement with the experimental results, with most predictions closely following the 1:1 line and remaining within the $\pm 20\%$ error band, indicating that the consideration of the kinematics of the critical re-entrant corner crack provides an effective basis for predicting the ultimate capacity of dapped-end connections. The VecTor2 nonlinear finite element model also demonstrated good agreement with the experimental results, with most predictions falling within the $\pm 20\%$ error band and successfully capturing the overall capacity trend and structural behaviour. Among the conventional analytical approaches, the PCI Design Approach [1] generally produced conservative predictions with relatively larger deviations from the experimental capacities. The classical Strut-and-Tie Model (STM) proposed by Schlaich and Schäfer [5] exhibited greater variability, with both conservative and unconservative predictions, indicating that the idealised load-transfer mechanism may not fully capture the complex behaviour of the disturbed region in dapped-end connections. Overall, the KBM provided the highest analytical prediction accuracy, while the validated VecTor2 model demonstrated comparable predictive performance, highlighting their potential for reliable assessment of the ultimate capacity of reinforced concrete dapped-end connections.

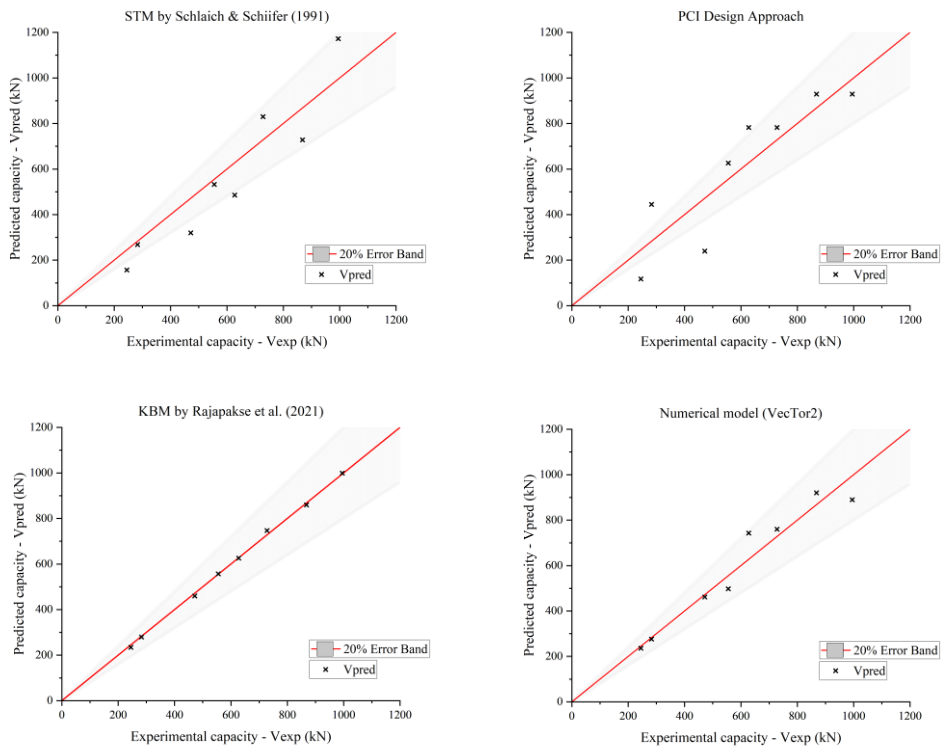


Figure 2: Comparison of experimental and predicted capacities for the analytical models and the nonlinear finite element model.

4. Conclusion

The Kinematics-Based Model (KBM) provided the most accurate analytical predictions, while the validated VecTor2 model showed comparable numerical performance. The PCI Design Approach and the classical strut-and-tie model exhibited greater deviations from the experimental results.

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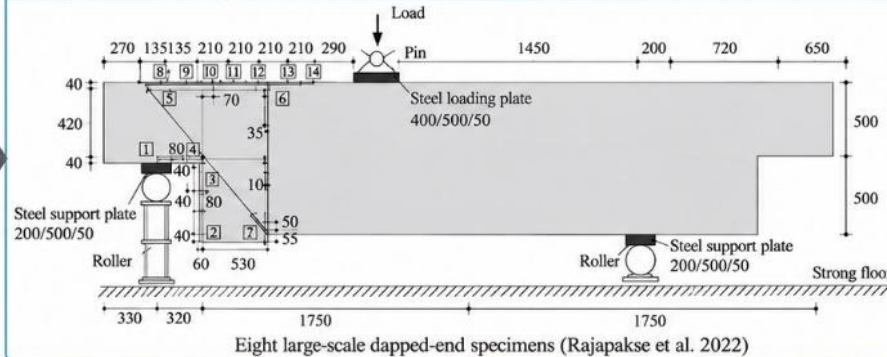
COMPARISON OF ANALYTICAL AND NUMERICAL MODELS FOR PREDICTING THE CAPACITY OF REINFORCED CONCRETE DAPPED-END CONNECTIONS

Motivation

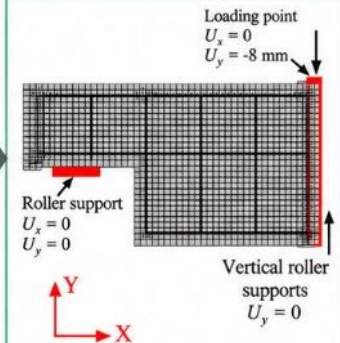


Dapped-end connections are widely used in precast concrete structures, but are vulnerable to inclined corner cracks and brittle failure.

Experimental Program



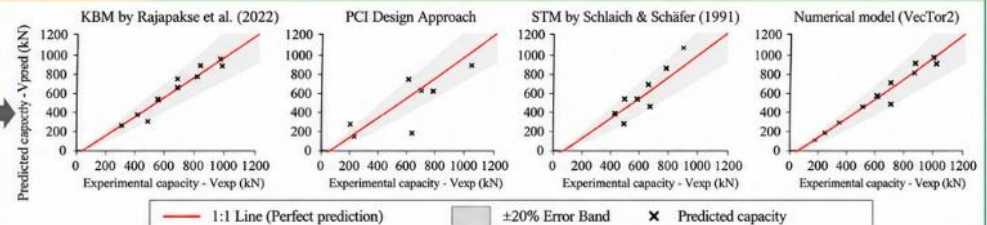
Numerical Model (VecTor2)



Analytical and Numerical Models

- Kinematics-Based Model (KBM)
Rajapakse et al. (2022)
- PCI Design Approach
(PCI, 2010)
- Strut-and-Tie Model (STM)
Schlaich and Schäfer (1991)
- Numerical Model
(VecTor2)

Predicted vs Experimental Ultimate Capacity



Key Finding

The Kinematics-Based Model (KBM) provided the most accurate analytical predictions, while the validated VecTor2 model demonstrated comparable numerical performance. Among conventional methods, the PCI approach was conservative and the classical STM showed the greatest variability.

SEISMIC VULNERABILITY ASSESSMENT OF RESIDENTIAL BUILDINGS IN SRI LANKA

P.H.T. Punchihewa^{1*}, H.G.H. Damruwan¹, C.S. Lewangamage¹

¹ Department of Civil Engineering, University of Moratuwa, Moratuwa

**Corresponding author: punchihewa2001@gmail.com*

Abstract

Although Sri Lanka is generally considered to be in a low-seismicity region, historical records and recent hazard studies indicate that potentially damaging earthquakes may occur, while non-engineered masonry housing may remain vulnerable to such loading. This study assessed typical single-storey residential buildings using ETABS-based numerical modelling and qualitative reduced-scale prototype testing. Three representative models were analysed as masonry-only and with concrete columns, beams and lintels. Equivalent static and response spectrum analyses were used to evaluate base shear, roof drift and shell-stress concentrations, while theoretical time histories were used for shaking-table testing. The masonry-only model, Model 02(A), showed the highest drift and lowest stiffness, with critical stresses around openings, corners and wall junctions. Concrete elements reduced the X- and Y-direction roof drifts of the model by 90.1 percent and 84.8 percent, respectively. Rammed earth (RE) prototype testing also showed lower wall-top displacement after improvement. The findings demonstrate that building layout, wall connectivity and opening arrangement strongly influence seismic response and that appropriate concrete elements can improve the behaviour of typical masonry houses.

Keywords: Unreinforced masonry, Numerical analysis, Rammed earth prototype testing, Shaking table testing

1. Introduction

Sri Lanka is located away from major active plate boundaries and is generally classified as a low-seismicity country. Nevertheless, historical earthquake records [1] and probabilistic hazard studies [3] indicate that potentially damaging ground shaking may occur. This is important for low-rise masonry housing, where common deficiencies include unreinforced openings, weak wall connections, poor mortar joints and missing tie elements [2]. This study evaluates the influence of building layout, wall continuity, openings and structural detailing on seismic response by comparing masonry-only and concrete-improved numerical models supported by reduced-scale prototype testing.

2. Methodology

2.1 Identification of Construction Practices and Model Selection

The methodology reviewed previous studies and field observations to identify typical Sri Lankan residential construction practices and common deficiencies [2]. Three single-storey layouts were selected as shown in Figure 1: Model 01 as a compact reference model, Model 02 as a realistic four-bedroom house, and Model 03 as a smaller two-bedroom layout suitable for prototype testing.

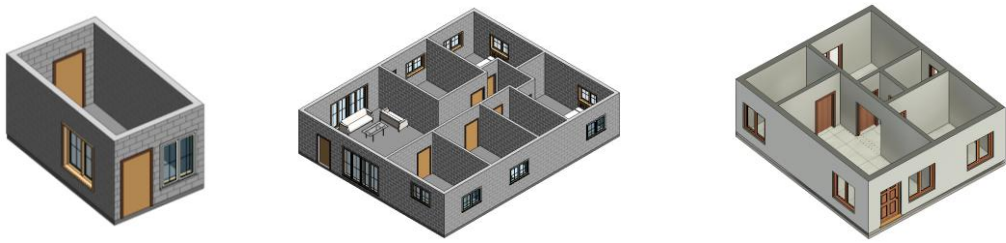


Figure 1: Representative residential building models: Model 01, Model 02, Model 03.

2.2 Numerical Analysis

Each layout was modelled in ETABS as Series A, representing masonry-only construction, and Series B, incorporating concrete elements. Load-bearing walls were idealised using shell elements. Modal, equivalent static and response spectrum analyses were performed in both principal directions using Sri Lanka's seismic conditions based on Eurocode 8, IS 1893 and previous Sri Lankan studies [3]. Fundamental period, base shear, roof drift, stiffness and shell stresses were evaluated. The roof structure was not explicitly modelled; therefore, its contributions to mass distribution, diaphragm action and lateral stiffness were not represented.

2.3 Experimental Analysis

Two 1:10 scale RE models were used to compare masonry-only and concrete-improved configurations [4]. The specimens were anchored to a shaking table and instrumented at the table base, model base, front-wall top and window region. Theoretical acceleration time histories from 0.02 g to 0.50 g were applied for 60 s in one horizontal direction. As no visible cracking occurred, the experiment was interpreted qualitatively rather than as a prediction of full-scale behaviour.

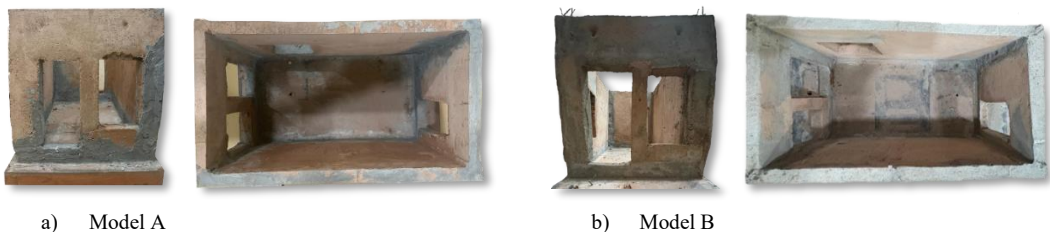


Figure 2: Prepared physical models for shaking table analysis.

3. Results and Discussion

The results were interpreted using limiting stresses of 1.5 MPa in compression and 0.1 MPa in tension and shear [5]. As masonry and RE are weak in tension, shell-stress contours were used to identify critical regions around openings, corners and wall junctions. Model behaviour was compared using period, base shear, roof drift, stiffness and stress distribution.

- Compression $\sigma_c \leq 1.5 \text{ MPa}$, Tension $\sigma_t \leq 0.1 \text{ MPa}$, Shear $\tau_{allow} \leq 0.1 \text{ MPa}$ ($\approx 0.065\sigma_c = 0.0975 \text{ MPa}$)

3.1 Numerical Analysis Results

Shell-stress contours consistently identified openings, narrow wall segments, wall junctions, external corners and unsupported upper panels as critical regions. In realistic layouts, interaction between internal walls and adjacent openings altered force transfer and stress

distribution; therefore, simplified rectangular models did not fully represent the behaviour of typical houses.

Table 1: Percentage change from masonry-only model to concrete-element model.

Model	Δ Period	FZ change	EQx shear	EQy shear	Δ X drift	Δ Y drift
Model 01	-2.4%	-2.6%	+4.1%	+5.2%	+0.0%	+0.0%
Model 02	-68.5%	+81.3%	+75.1%	+127.2%	-90.1%	-84.8%
Model 03	-1.6%	+15.7%	+8.7%	+6.4%	-19.7%	-25.9%

The addition of concrete columns, beams and lintels generally increased lateral stiffness and reduced roof drift, with the magnitude of improvement depending on wall layout and opening configuration. Changes in base shear were associated with increased mass and stiffness. Overall, the improved models showed better deformation control and load-transfer behaviour.

3.2 Experimental Analysis Results

The reduced-scale investigation compared masonry-only Model 01(A) with concrete-improved Model 01(B). The highest response occurred at the front-wall top and near the window opening, while Model 01(B) showed a lower displacement response. No visible cracking occurred and dominant-frequency changes were small; therefore, the experiment provides qualitative evidence of improved deformation control rather than full-scale damage behaviour.

4. Conclusions

Typical Sri Lankan masonry houses may be vulnerable to seismic loading because of unreinforced openings, weak wall connections, poor mortar joints and missing tie elements. Numerical results showed that wall layout, opening arrangement and internal-wall connectivity strongly influence stiffness, drift, load transfer and stress concentration. Concrete columns, beams and lintels generally improved structural continuity and reduced lateral deformation. Shaking table testing also showed a lower displacement response in the improved model, although no visible cracking occurred. The findings highlight the importance of representative building layouts, strengthened openings, improved wall connections and continuous tie elements for safer residential construction in Sri Lanka.

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SEISMIC VULNERABILITY ASSESSMENT OF RESIDENTIAL BUILDING IN SRI LANKA

Numerical and Reduced-Scale Prototype Analysis

KEY FINDINGS

Building layout, openings and wall connectivity strongly influenced seismic response. Concrete columns, beams and lintels improved structural continuity, increased stiffness and reduced lateral deformation. Reduced-scale testing also showed lower displacement after improvement, supporting the numerical findings.

1. MOTIVATION

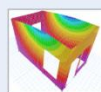


Sri Lanka low-rise masonry houses often have unreinforced openings, weak connections, poor mortar joints and missing tie elements, leading to high vulnerability.[1,2]

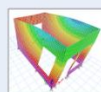
2. METHODOLOGY

Model Development in ETABS

Series A
Masonry-only



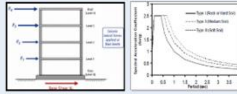
Series B
With Concrete Elements



Three single-storey layouts:
Model 01 (reference), Model 02 (4-bedroom),
Model 03 (2-bedroom).[3]

Numerical Analysis

Equivalent Static Response Spectrum



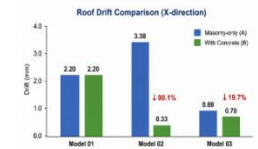
Outputs: Period, Base shear, Roof drift, Stiffness, Shell-stress distribution.[4]

Reduced Scale Prototype (1:10 Scale)



Model 01 Shaking table testing with theoretical acceleration time histories (0.02g - 0.05g).[4]

3. KEY RESULTS



Period Reduction

Model 01: -30%
Model 02: -68%
Model 03: -2%

Stiffness Reduction

Model 01: +4.1%
Model 02: +81.3%
Model 03: +15.7%

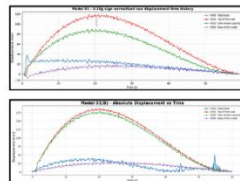
4. EXPERIMENTAL RESPONSE (SHAKING TABLE)

Shaking Table Configuration



R201 shaking table; model fixed with four bolts; excitation in one horizontal direction.[4]

Displacement Response

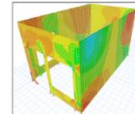


Wall-top displacement reduced.

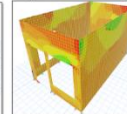
No visible cracking observed.[5]

4. NUMERICAL ANALYSIS

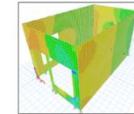
Shell -Stress Contours (Masonry-only - Model 01)



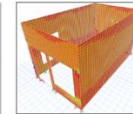
S12: DL+LL+RSx
Model 01(A)



S11: DL+LL+RSx
Model 01(B)



S12: DL+LL+RSx
Model 01(C)



S11: DL+LL+RSx
Model 01(D)

High stress concentration occur around openings, corners, wall junctions and unsupported wall regions.[4]

- Wall layout, openings and connections strongly influence seismic behavior.
- concrete columns, beams and lintels greatly improve stiffness and reduce lateral deformation.
- Prototype tests confirm lower displacement after strengthening; results are qualitative rather than full-scale.
- Findings support preliminary vulnerability assessment and practical construction guidance for safer housing in Sri Lanka

5. CONCLUSION

OPTIMAL DESIGN OF STEEL PORTAL FRAMES USING HETEROGENEOUS GRAPH NEURAL NETWORKS

B.H.I. Sandamayura¹, H.M.S.T. Herath^{1*}

¹ University of Moratuwa, Moratuwa, Sri Lanka

**Corresponding author: sumuduh@uom.lk*

Abstract

Steel portal frames are the predominant structural system for industrial warehouses, yet conventional design relies on iterative finite element workflows that are time-consuming and often produce material-intensive solutions. This study presents a machine learning framework using Heterogeneous Graph Neural Networks for cost-optimal, Eurocode 3-compliant design of steel portal frame warehouses. A three-phase methodology was adopted: automated generation of 1,248 synthetic warehouse models through the SAP2000 Open Application Programming Interface, heterogeneous graph representation distinguishing joint, primary frame, secondary frame, and area nodes, and training of a surrogate model, HetSteelFEA, alongside five specialised feed-forward networks, collectively termed SectionOptNN, for structural section classification. HetSteelFEA achieved a mean absolute percentage error of 2.36 percent and a coefficient of determination of 0.9734, with a 30-fold computational speedup over conventional finite element analysis. The SectionOptNN pipeline achieved an overall section classification accuracy of 93.62 percent. The integrated optimisation framework identified warehouse layouts achieving 10 to 45 percent reductions in total steel weight compared with rule-of-thumb configurations. These results confirm that topology-aware surrogate modelling is a viable and computationally efficient alternative to iterative finite element-based design, offering rapid, code-compliant layout screening for industrial structural engineering practice.

Keywords: Structural optimisation, Machine learning, Surrogate modelling, Warehouse layout, Code compliance

1. Introduction

Steel portal frames are the dominant structural system for industrial warehouses because of their long clear spans, rapid construction, and efficient use of standardised sections. In import-dependent economies such as Sri Lanka, where structural steel forms a major portion of project cost, minimising total steel weight without compromising safety or code compliance [1] is a critical design objective. Conventional design involves repeated member resizing and layout adjustment within commercial finite element software, a process that is time-consuming and explores only a small fraction of the available design space, particularly since instability-sensitive phenomena such as lateral-torsional and flexural buckling are difficult to generalise using simple empirical rules. Recent graph-based deep learning methods show promise for structural response prediction by preserving physical connectivity [2], yet most existing applications use tabular representations that are topology-blind and cannot capture the load paths intrinsic to portal frame warehouses. This study addresses that gap by developing a heterogeneous graph-based surrogate framework that predicts internal actions and optimum sections directly from structural topology, integrated into a layout optimisation loop that identifies cost-optimal, code-compliant configurations at a fraction of the computational cost of iterative finite element analysis.

2. Methodology

An automated Python workflow was developed using the SAP2000 Open Application Programming Interface to generate, analyse, and optimise 1,248 parametric warehouse models, varying span (15–30 m), eave height (6–12 m), bay spacing (6–12 m), length (24–96 m), and bracing topology (X- and K-bracing) under Eurocode 3 [1]-integrated gravity and wind loading (wind speed = 23 m/s) [3]. Each warehouse was represented as a heterogeneous graph distinguishing joint, primary frame (column, rafter, strut, bracing), secondary frame (purlin, girt), and area nodes, connected through joint-to-frame, frame-to-frame, area-to-frame, and secondary-system edges that preserve the true structural topology and load paths (Figure 1).

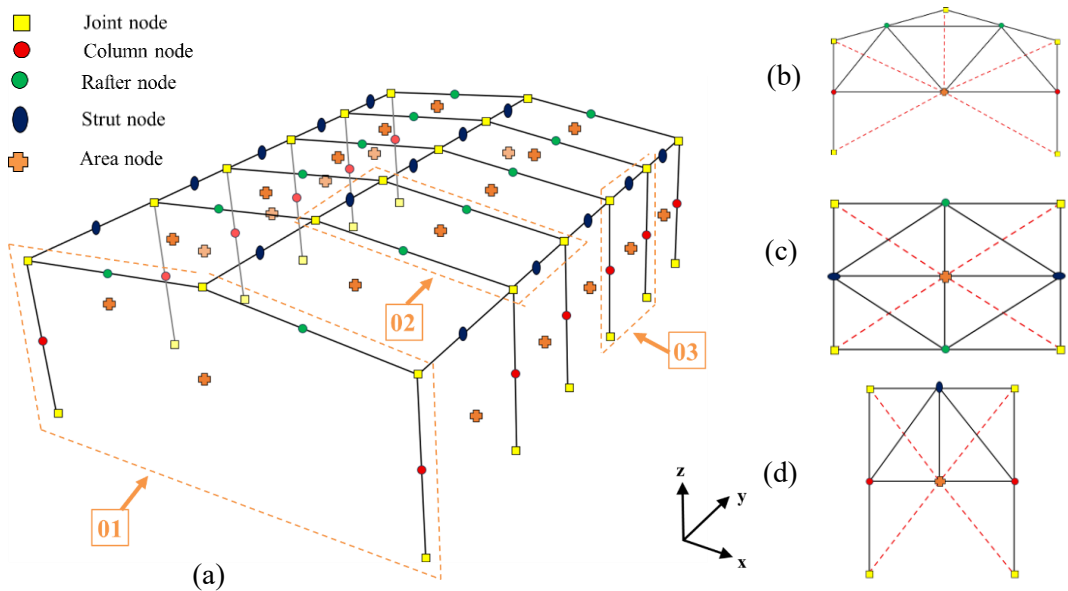


Figure 1: Graph representation and connectivity relationships (a) 3D view (b) Front view (plane 01) (c) Top view (plane 02) (d) Side view (plane 03).

A heterogeneous graph attention network, HetSteelFEA, with four edge-aware message-passing layers over member stiffness and connection type, was trained to predict six internal force components (maximum and minimum bending moment, shear force, and axial force) for each primary member. These forces were passed to five specialised feed-forward networks, collectively SectionOptNN, which classify optimum catalogue sections for columns, rafters, struts, lateral bracing, and roof bracing, since a single classifier could not adequately separate governing failure modes such as lateral-torsional from flexural buckling. The surrogate was embedded within a layout optimisation loop ranking candidate bay-spacing and bracing configurations by predicted weight, evaluating each candidate layout in under 30 seconds.

3. Results and Discussion

HetSteelFEA achieved a mean absolute percentage error of 2.36 percent and a coefficient of determination of 0.9734 against SAP2000 ground-truth actions, with an absolute error of 5.13 kN or kN.m, well within preliminary design tolerances given eave bending moments of 200–800 kN.m. Training and validation losses converged smoothly, confirming that the heterogeneous representation generalises load paths rather than memorising training geometries. The five SectionOptNN models achieved accuracies from 84.3 percent (rafters) to

98.1 percent (columns), with an overall weighted accuracy of 93.62 percent; near-miss predictions typically correspond to an adjacent catalogue section with a marginal mass penalty below 5 percent, acceptable for optimisation-stage screening.

Applied to a case-study warehouse (20 m span, 8 m eave height, 40 m length), the framework evaluated twenty candidate layouts and identified a variable-bay, K-braced configuration (8, 6, 6, 6, 6, 8 m; Figure 2) as optimal, reducing total steel mass from 20.07 t (equal-bay baseline) to 14.53 t, a 28 percent saving. Across all tested configurations, the surrogate-assisted search achieved 10–45 percent weight reductions relative to rule-of-thumb layouts, evaluating each candidate in under 30 seconds and delivering an overall 30-fold speedup over iterative finite element analysis. These findings show that topology-aware surrogate modelling can reliably differentiate between competing layouts even without reproducing the exact optimum for every member.

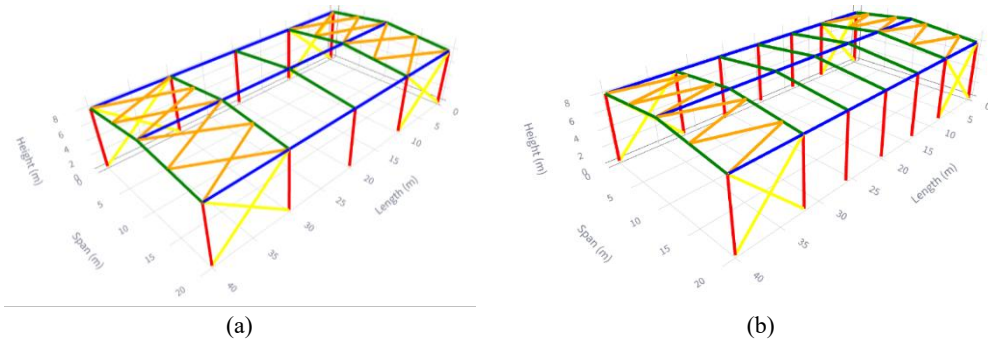


Figure 2: Case-study warehouse layouts (a) standard equal-bay baseline (X-bracing, 20.07 t) and (b) AI-optimised variable-bay K-braced layout (14.53 t, 28% weight reduction).

4. Conclusion

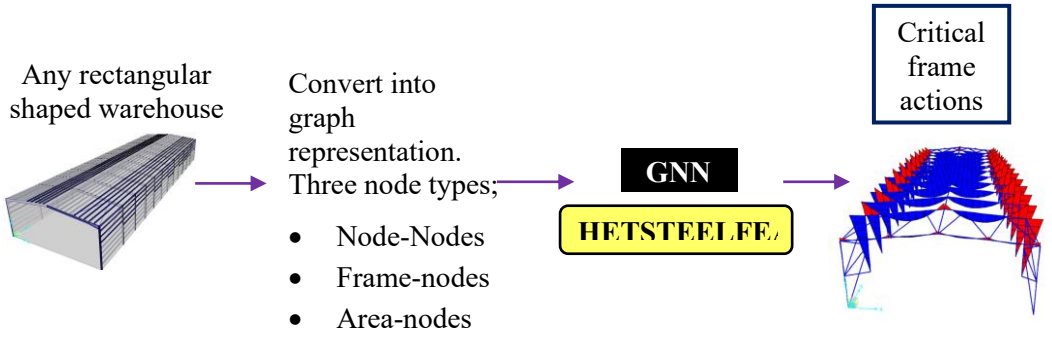
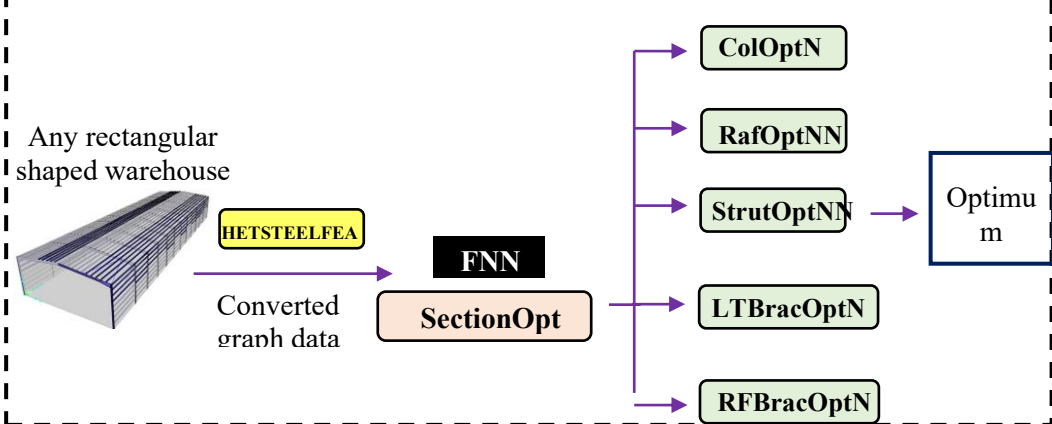
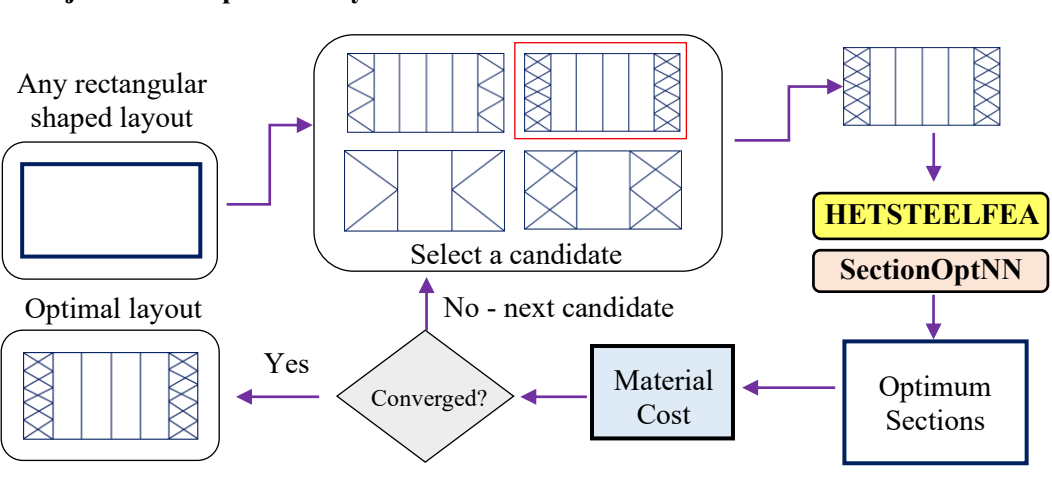
This study demonstrates that replacing rule-of-thumb configurations with layout-optimised models achieves a 10 to 45 percent steel weight reduction under Eurocode 3 compliance, while integrating heterogeneous graph neural networks delivers a 30-fold speedup over conventional finite element analysis. Future work will extend the framework to tapered members, semi-rigid connections, and non-rectangular plan geometries.

Acknowledgements

The authors would like to acknowledge the funding received from the University of Moratuwa Senate Research Committee grant SRC/LT/2025/15 for the successful completion of this work.

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Objective 1 – Critical action prediction**Objective 2 – Optimum section prediction****Objective 3 – Optimum layout selection**

SEISMIC PERFORMANCE OF REINFORCED CONCRETE BUILDINGS WITH SHEAR WALLS UNDER STRUCTURAL IRREGULARITIES

S. Nirushan¹, H.G.H. Damruwan¹, C.S. Lewangamage¹

¹ Department of Civil Engineering, University of Moratuwa, Moratuwa, Sri Lanka

**Corresponding author: sriniru29@gmail.com*

Abstract

Structural irregularities can significantly alter the seismic response of reinforced concrete buildings by modifying stiffness, mass distribution and load paths. This study evaluates the influence of structural irregularities and shear wall placement on the seismic performance of mid-rise reinforced concrete buildings in Sri Lanka. A detailed literature review identifies a limited body of experimental and numerical research addressing the combined effects of shear wall arrangement and structural irregularity within the Sri Lankan construction context. To address this gap, a finite element (FE) model of a five-storey reinforced concrete building is developed in ETABS software and assessed using the seismic provisions of Eurocode EN 1998-1:2004. Different shear wall arrangements and horizontal and vertical irregular configurations are investigated through response spectrum analysis, with a particular emphasis on the fundamental period, lateral displacement, inter-storey drift, and torsional response. The results indicate that the introduction of shear walls significantly improves lateral stiffness and reduces both the fundamental period and lateral displacement, with reductions exceeding 40% across the configurations investigated. Furthermore, irregular configurations involving corner-placed shear walls and discontinuities in the structural grid produce less favourable responses, primarily due to increased eccentricity and torsional effects. These results provide a strong foundation for future work, emphasising that scaled-down experimental testing is essential to bridge the gap between numerical predictions and physical structural behaviour.

Keywords: Shear walls, Seismic performance, Torsional response, Structural irregularity

1. Introduction

Earthquakes are among the most destructive natural hazards, causing severe losses to life, economic productivity, and social stability. Infrequent occurrence in many regions often leaves preparedness inadequate, resulting in catastrophic damage. This has driven researchers to prioritise advances in seismology and earthquake engineering, with experimental, numerical, and machine learning-based approaches now key to understanding structural behaviour under seismic loading. Growing urban density and high-rise construction have heightened seismic risk awareness: over the past two decades, 313 earthquakes exceeding magnitude 7.0 have been recorded worldwide, mostly in developing countries [1]. Sri Lanka has traditionally been classified as a low-seismicity region within the northern Indian Ocean, with hazards linked to tectonic activity along the Indo-Australian Plate boundaries [2]. However, its documented seismic history and increasingly frequent recent tremors suggest an evolving risk profile [3].

Shear walls are central to seismic-resistant design, providing the lateral stiffness and strength needed to resist earthquake forces and limit inter-storey drift. Research has optimised their effectiveness through geometric modification, improved material use, and energy-dissipation mechanisms such as dampers, improving seismic energy dissipation by around 45% over conventional RC frames [4]. Beyond wall quantity, strategic placement is often more cost-

effective than increasing wall numbers [5]. Symmetrical distribution is particularly effective at mitigating torsional effects, giving buildings with well-distributed shear walls superior seismic behaviour and structural efficiency. Since perfectly symmetrical building configurations are not always feasible in practice, the combined effects of shear wall functionality and spatial arrangement on seismic performance remain insufficiently explored. This study addresses this gap through a numerical investigation of a five-storey building representative of Sri Lanka's urban mid-rise residential construction.

1.1 Aim and Objectives

The aim of this research is to evaluate the influence of shear wall configurations and structural irregularities on the seismic performance of mid-rise reinforced concrete buildings in Sri Lanka and to identify suitable shear wall arrangements for improving their seismic response. This aim will be achieved by undertaking the objectives below.

1. Review existing research and relevant seismic design provisions related to shear wall configurations and structural irregularities in reinforced concrete buildings.
2. Develop numerical models of representative mid-rise reinforced concrete buildings with different shear wall arrangements and structural irregularities under seismic loading conditions relevant to Sri Lanka.
3. Evaluate and quantify the effects of different shear wall configurations on key seismic response parameters, including lateral stiffness, storey displacement, inter-storey drift, natural period, and torsional response.
4. Identify suitable shear wall arrangements for improving the seismic performance of mid-rise reinforced concrete buildings and provide recommendations for their effective placement in buildings relevant to Sri Lankan conditions.

2. Methodology

To evaluate the influence of shear wall arrangement and structural irregularities on seismic performance, a numerical case study was carried out on a representative mid-rise residential building using ETABS software. The model captures typical Sri Lankan construction practice while incorporating European seismic codes, enabling a systematic comparison of different shear wall configurations and irregularity types under earthquake loading. The different arrangements used are summarised in Figure 1.

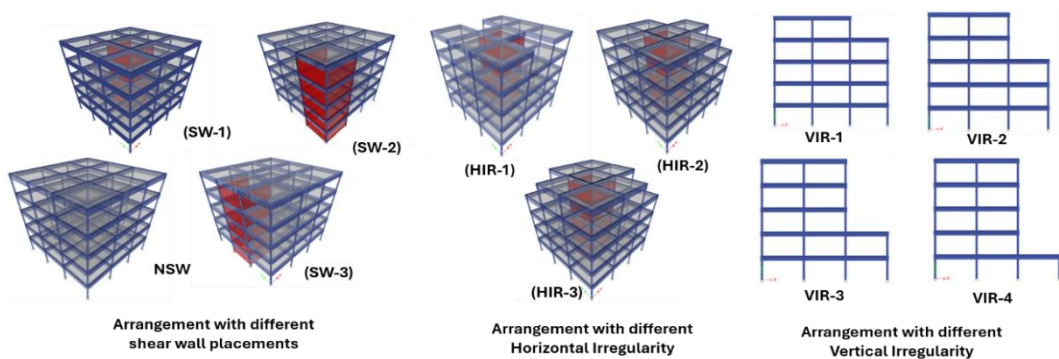


Figure 1: Arrangement used in numerical analysis.

3. Key Findings and Conclusions

The horizontal and vertical irregularity results reveal a consistent pattern: geometric irregularities mainly redistribute torsional demand rather than significantly altering overall stiffness, though the two types affect dynamic behaviour differently. The summarised displacement and drift ratio values are presented in Figure 2. The following conclusions can be drawn from the numerical study:

- Adding a centrally located shear wall system significantly improved lateral stiffness, cutting the fundamental period by 59% and maximum displacement by 80%; all tested configurations achieved over 40% reductions, with the central core arrangement giving the most balanced seismic performance and recommended where architecture allows.
- Corner-located shear walls performed worst, showing greater eccentricity and torsional effects (25.1% torsional mass participation); horizontal plan irregularities showed a similar trend, so eccentric shear wall placement should generally be avoided unless torsion is actively controlled through balanced stiffness or supplemental damping.
- Removing corner sections of the floor plan (horizontal irregularity) did not trigger significant torsional behaviour in the first two vibration modes, though the resulting increase in eccentricity did affect translational response, producing the highest lateral displacement among the irregular cases tested.
- Vertical irregularities from removing upper storeys had little effect on the fundamental period but reduced lateral displacement due to the building becoming shorter and lighter; however, torsion accounted for over 25% of mass participation, showing increased torsional sensitivity that requires careful design of vertical setbacks.

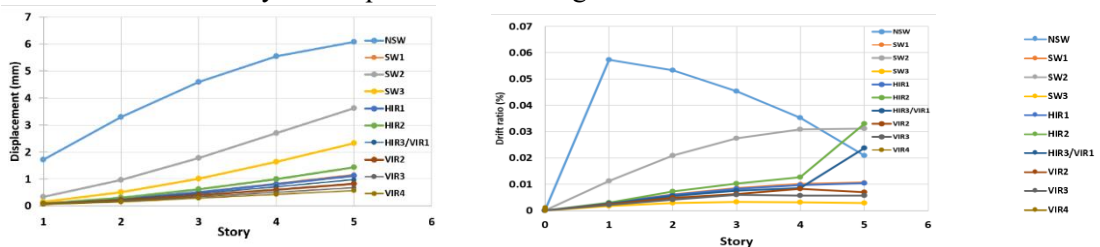
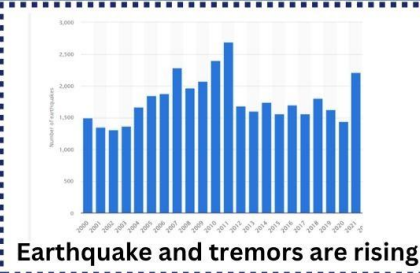


Figure 2: Displacement and drift ratio (%) behaviour of different

References

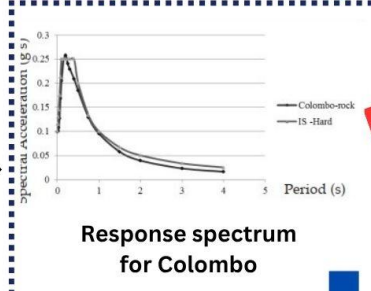
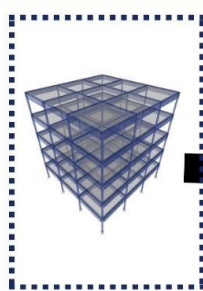
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Seismic Performance of Reinforced Concrete Buildings with Shear Walls under Structural Irregularities



- Frame shear wall systems enhance seismic energy dissipation
- Numerical studies conclude that the strategic positioning of shear walls is a more cost-efficient design strategy

Research methodology

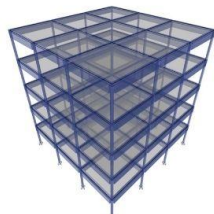


Numerical modelling

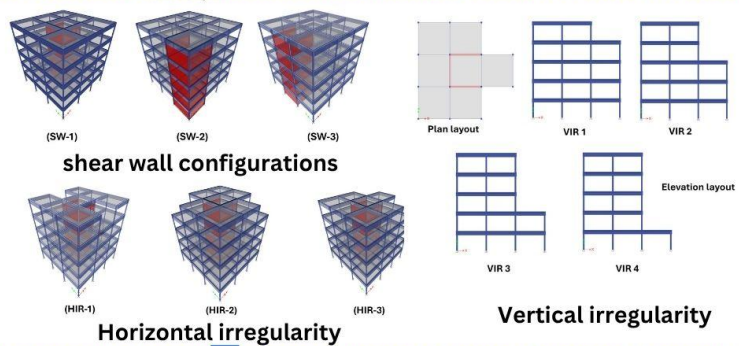


Since experimental testing of physical models is highly time-consuming and costly, the development of accurate numerical models is essential for efficiently evaluating structural behaviour

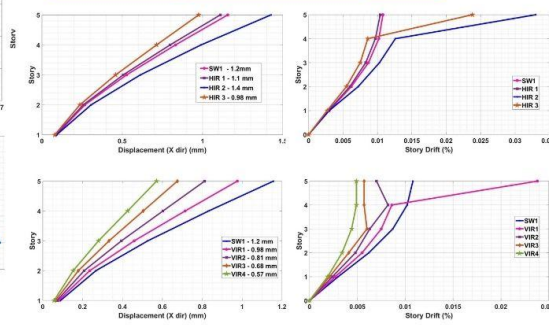
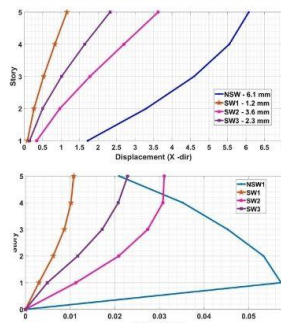
Parametric study



NSW
Control set up



Comparative Study



TRANSITION REGION CHARACTERISTICS OF COILED OPEN CROSS-SECTION THIN SHELL BOOMS

K.G.A.T. Gayashan¹, P.M. Ranathunge¹, H.M.Y.C. Mallikarachchi^{1*}

¹ University of Moratuwa, Katubedda, Sri Lanka

**Corresponding author: yasithcm@uom.lk*

Abstract

Coiled deployable booms offer lightweight structural support and high packaging efficiency for space systems, but the transition region between the flattened root and deployed section remains understudied. This study investigates the transition region behaviour of tape-spring and Triangular Rollable and Collapsible (TRAC) booms using a common nonlinear finite element framework. Boom height, width, transverse curvature, and strain-energy density were evaluated along the deployed length. Both booms showed rapid near-root recovery followed by gradual stabilisation, with edge regions recovering earlier than mid regions and most of the strain energy relaxing before full geometric recovery. A parametric study showed that transition length increases with subtended angle and transverse radius; the tape-spring response was nonlinear, whereas the TRAC response was approximately linear and more sensitive to radius. For baseline cross-sections, shorter deployed lengths modified curvature recovery, particularly for the TRAC boom. These findings provide transition-region metrics for informed root-guide assembly positioning and design.

Keywords: Tape-spring, TRAC boom, Curvature recovery, Root guide

1. Introduction

Coiled deployable booms provide lightweight and compact structural support for spacecraft systems such as solar sails, antennas, and instrument arrays [1]. During deployment, the boom cross-section gradually reforms over a finite axial distance, creating a transition region between the flattened root and the fully recovered section. The geometry and mechanical state of this region determine how load is transferred through the root and where usable sectional stiffness is re-established, making its characterisation important for root-guide assembly design and placement. Previous studies have identified stress concentration, material failure, and local buckling within the transition region of thin-shell deployable booms [2]. Nevertheless, the recovery of the deployed cross-section and its dependence on boom geometry and available deployed length remain insufficiently quantified. This study therefore characterises the transition region of open cross-section deployable booms using nonlinear finite element analysis. The investigation considers baseline geometric and energy recovery and the influence of deployed length on the transition region for the baseline cross-sections.

2. Numerical Model

Two representative open cross-section deployable booms, a tape-spring boom and a TRAC boom, were considered to represent different levels of sectional complexity. The tape spring consists of a single curved shell, whereas the TRAC boom comprises two curved flanges joined through a web. The principal geometric parameter values adopted for the two baseline models are summarised in Table 1. Both booms were assigned the same equivalent $\pm 45^\circ$ two-ply woven T300-1k/913 CFRP laminate, using the laminate ABD stiffness reported by Mallikarachchi

Table 1: Baseline finite element model definitions.

Parameter	Tape-spring	TRAC boom
Transverse radius (R)	20 mm	10.6 mm
Subtended angle (α)	90°	80°
Deployed length (L)	300 mm	
Web height (w_0)	-	8 mm
Shell thickness (t)	0.2 mm	

[3], to maintain a consistent material basis and isolate the influence of cross-sectional geometry. A common nonlinear finite element framework was developed in Abaqus/Standard using the Static General procedure with geometric nonlinearity. The booms were modelled with S4R shell elements, while spool and clamp components were treated as rigid bodies with appropriate contact interactions. Root flattening, contact activation, controlled clamp motion, and spool rotation generated the partially coiled root configuration. The framework was qualitatively validated against the characteristic tape-spring curvature-recovery response reported by Wang et al. [4]; the model reproduced the near-root disturbance and progressive recovery, after which the same approach was applied to the TRAC boom. Transition-region recovery was assessed using boom height (h), boom width (w), transverse curvature (κ), and strain-energy density, with the geometric definitions shown in Fig. 1.

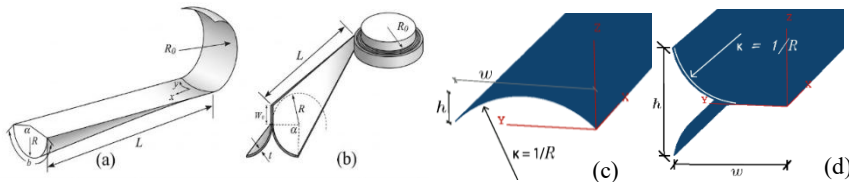


Fig. 1. Geometric parameters of (a) tape-spring and (b) TRAC boom and definitions of boom height h , boom width w and transverse curvature κ used for geometry extraction: (c) tape-spring and (d) TRAC boom models.

A local coordinate system was defined to preserve the longitudinal, transverse, and out-of-plane directions after coiling. Midline and edge paths were used for the tape spring, while separate midline and edge paths on both TRAC flanges, together with a web-edge reference path, were used for the TRAC boom. Coordinates, displacements, curvatures, and strain-energy density were extracted along these paths and processed against axial distance s from the root.

3. Results and Discussion

3.1 Base-Case Characterisation

The baseline models showed a rapid recovery close to the root followed by a more gradual approach to the fully deployed cross-section. For the tape-spring boom, height increased to a recovered value of approximately 5.85 mm, while width reduced to approximately 28.30 mm. The corresponding transition lengths obtained from height and width recovery were 101.7 mm and 101.8 mm, respectively, indicating very consistent global sectional recovery. The TRAC boom recovered to a height of approximately 17.5 mm and a width of approximately 18.4 mm, with transition lengths of 108.0 mm and 110.3 mm from the height and width profiles, respectively. Transverse-curvature recovery, shown in Fig. 2, further revealed that recovery was not uniform across either section. For the tape spring, the edge path approached the recovered curvature of about 0.05 mm^{-1} earlier than the midline. A similar but more pronounced path-dependent response occurred in the TRAC boom, where the flange edges recovered earlier than the mid-paths and approached a final curvature of approximately 0.094 – 0.095 mm^{-1} . Strain-energy-density results showed that both booms stored the highest deformation energy near the disturbed root, followed by a progressive decay along the deployed length. At the adopted meshes, the tape spring showed more localised energy recovery than the TRAC boom.

3.2 Parametric Study

For the tape spring, increasing α from 70 to 110 degrees raised the transition length (L_{tr}) from about 81 to 138 mm, while increasing R from 15 to 25 mm raised it from about 81 to 144 mm. Both relations were nonlinear, with low-sensitivity intervals near $\alpha = 83$ – 90° and $R = 17$ – 18

mm followed by a sharp post-baseline increase. TRAC trends were approximately linear: L_{tr} increased from 89 to 129 mm for $\alpha = 70^\circ$ - 90° and 79 to 142 mm for $R = 8.0$ - 13.2 mm. The steeper radius trend identifies R as the dominant TRAC parameter within the investigated range.

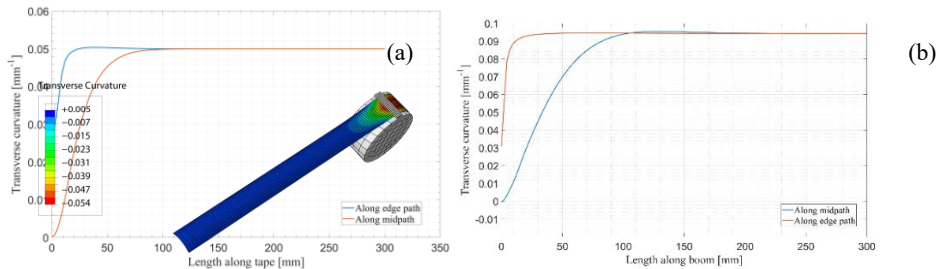


Fig. 2. Baseline curvature-recovery profiles of the (a) tape-spring and (b) top flange of TRAC boom.

3.3 Effect of Deployed Length

Deployed length was varied while retaining the baseline cross-sections in Table 1. Transverse curvature profiles were compared with corresponding reference models having 500 mm deployed length. This comparison assessed how deployed length influences cross-sectional recovery along the boom. Shorter lengths produced greater near-root deviations. For the tape-spring, deviations were localised at a point nearly 30 mm away from the root and diminished after 110 mm as deployed length increased. For the TRAC boom, deviations peaked at nearly 50 mm away from the root and persisted to about 160 mm, exceeding its 108-110 mm geometry-based transition length. These results indicate that the transition-region response during deployment can extend beyond the transition length identified from the fully deployed geometry, particularly for the TRAC boom.

4. Conclusions

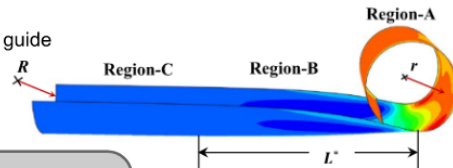
This study characterised the transition region of tape-spring and TRAC booms using geometric and strain-energy measures. Both booms showed rapid near-root recovery followed by gradual, non-uniform sectional stabilisation. Transition length increased with transverse radius and subtended angle, with the TRAC boom showing greater sensitivity to radius. Baseline curvature recovery depended on deployed length, particularly for TRAC. Overall, the results show that transition-region behaviour depends on both cross-sectional geometry and deployment state, supporting more informed root-guide positioning and design.

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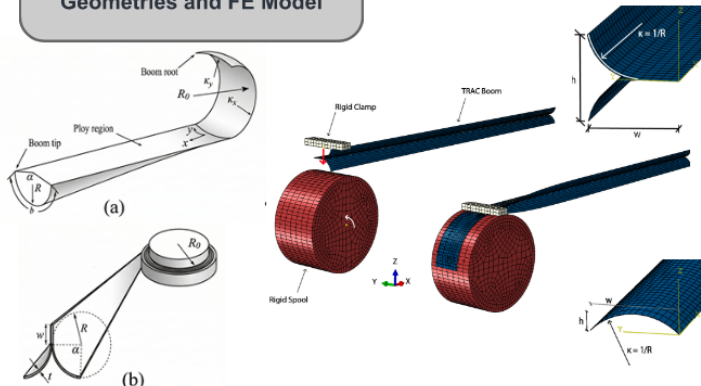
Transition Region Characteristics of Coiled Open Cross-Section Thin Shell Booms

- The transition region (Region-B), where the boom cross-section gradually recovers from the flattened coiled (Region-A) state to the fully deployed (Region-C geometry of deployable booms, remains underexplored and not properly characterized
- Directly affect the root guide designs and placement



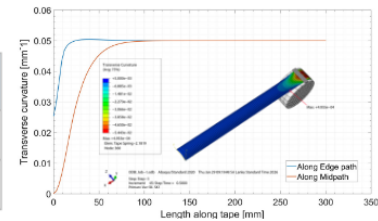
Problem & Significance

Geometries and FE Model



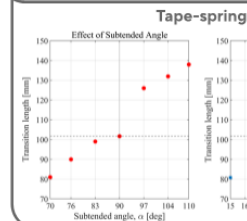
Base-Case Characterization

Boom type	Geometry Ltr	Energy Ltr
Tape-spring	~102 mm	~60 mm
TRAC boom	~110 mm	~100 mm



Edge regions recover before the midline, confirming non-uniform cross-sectional recovery; therefore, the longer geometry-based transition length should govern root-guide placement.

Parametric Study



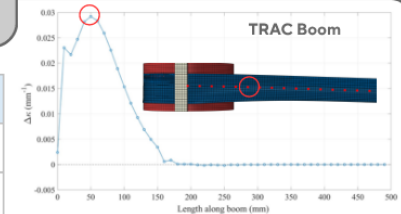
TRAC Boom

	Range	Ltr change	Trend
α	70°-90°	89→129 mm	linear, lower
R	8.0-13.2 mm	79→142 mm	linear, dominant

Increasing α or R extends the transition region; the tape-spring response is non-linear, while the TRAC boom is more radius-sensitive.

Effect of Deployed Length

Tape-spring	Result
Peak $\Delta\kappa$	~0.008 mm ⁻¹
Peak station	30 mm from root
Affected zone	~110 mm



TRAC shows a larger peak deviation (~0.028 mm⁻¹ at 50 mm) and a wider affected zone (~160 mm), indicating stronger root influence during deployment.

Design implication

Transition length defines the stable support region, parametric sensitivity controls preliminary root-guide sizing, and deployed-length deviation identifies stress-critical zones during deployment.

HYBRID DIC-IRT IMAGING FOR FULL-FIELD THERMO-MECHANICAL DEFORMATION MEASUREMENT

V.O. Ratnayake¹, P.M. Ranatunga¹, H.M.Y.C. Mallikarachchi^{1*}

¹ University of Moratuwa, Katubedda, Sri Lanka

**Corresponding author: yasithcm@uom.lk*

Abstract

Thin and lightweight structures can exhibit complex thermo-mechanical behaviour when subjected to spatially non-uniform thermal loading. Localised or radiative heating may generate temperature gradients that cause differential thermal expansion, bending, warping and transient instabilities, while the resulting deformation may in turn alter the thermal loading experienced by the structure. Characterising such behaviour therefore requires full-field measurements of both temperature and deformation, which cannot be adequately obtained using discrete contact sensors alone. This study presents a hybrid imaging system combining digital image correlation with infrared thermography for synchronised, non-contact full-field measurement of surface temperature and 3D deformation. The individual subsystems were calibrated and validated before being integrated for experiments under non-uniform radiant heating. Subsequent testing enabled simultaneous full-field observations, revealing thermally induced out-of-plane deformation and transient response behaviour. The validation results demonstrate the suitability of the developed optical sensing system for investigating coupled thermo-mechanical behaviour. Using accessible hardware and custom processing, the proposed method produces rich full-field datasets useful for advanced experimental mechanics.

Keywords: Thermo-mechanical characterisation, Full-field measurements, Digital image correlation, Infrared thermography

1. Introduction

From high-temperature material testing to lightweight structures operating in severe thermal environments, accurate interpretation of structural response often depends on the ability to measure coupled temperature and deformation fields simultaneously [1], [2]. Non-uniform thermal loading can induce differential expansion, curvature changes and instabilities in slender or lightweight structures. Capturing these responses can be challenging with discrete contact sensors, which may not adequately reveal local gradients or spatially heterogeneous deformation. Digital image correlation (DIC) provides non-contact full-field displacement and strain measurements, whereas infrared thermography (IRT) captures spatially resolved surface temperature, making their combined use attractive for thermo-mechanical experiments. This need is particularly relevant to lightweight deployable structures exposed to radiant heating, where deformation can in turn alter the effective thermal loading condition [3]. However, practical implementation requires reliable calibration, image processing, temporal correspondence and spatial synchronisation between the two imaging systems. The present study develops and experimentally demonstrates a hybrid DIC-IRT imaging system through coupled radiant heating experiments, enabling synchronised thermal and deformation fields for full-field thermo-mechanical characterisation of slender structures where deformation may influence the imposed thermal condition.

2. Experimental Methodology

The stereo-DIC system used two 8 MP cameras fitted with 5-50 mm lenses and arranged at an included angle of approximately 30 degrees. A 5 mm checkerboard target was imaged from 40-50 poses and calibrated in MATLAB using Zhang's method [4]. The in-house stereo-DIC system was then verified by translating a speckled concrete specimen through a 200 mm rigid-body motion [5]. A polygon-based region of interest was used to maintain tracking of the specimen surface. A HIKMICRO Mini2 V2 IR thermal camera was used for surface temperature measurements. K-type thermocouples were first calibrated against a reference thermometer and subsequently used to validate the IR measurements. Initial validation was performed on an aluminium strip partially immersed in heated water to generate a temperature gradient. A second validation was performed under the same 1 kW halogen heating arrangement subsequently used for the coupled experiment, ensuring the system was assessed under representative surface emissivity and heating conditions.

For the coupled test, a 320 mm × 40 mm × 0.3 mm aluminium strip was clamped at one end and locally heated near the free end using the halogen source, as shown in Figure 1. The surface was coated with a matte black base layer and a random white speckle pattern required for the DIC tracking. The stereo cameras measured 3D deformation, while the IR camera recorded the surface temperature field, with an emissivity of 0.97 set for the coated surface. A calibrated thermocouple and KEYENCE IL-065 laser displacement sensor provided point references for temperature and tip displacement, respectively. Glare and non-uniform illumination in the stereo images were reduced using a MATLAB preprocessing routine incorporating Gaussian background normalisation and contrast-limited adaptive histogram equalisation. Temporal correspondence was established during post-processing using acquisition time and sequence order. The IR field was spatially mapped onto the DIC measurement domain using corresponding specimen edges and corners through a 2D projective transformation, producing spatially synchronised datasets at matched time steps.

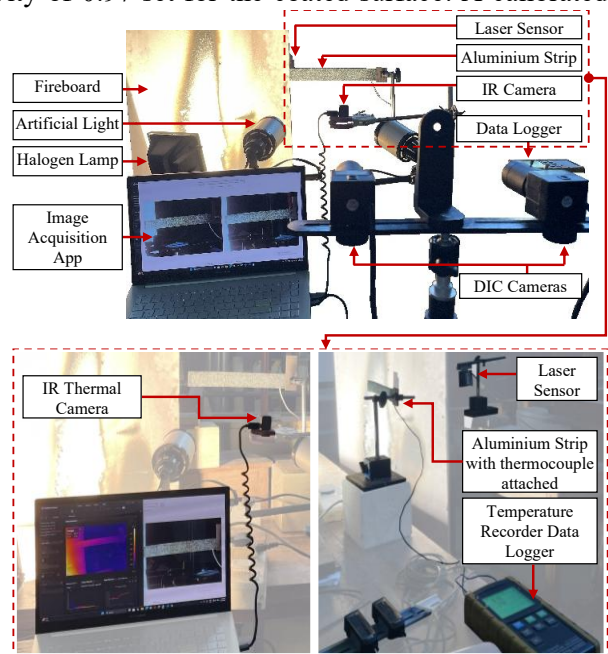


Figure 1: Coupled DIC-IRT experimental setup.

3. Results and Discussion

Prior to the coupled testing, the performance of the DIC and IRT systems was assessed and confirmed satisfactory. Stereo calibration produced a mean reprojection error of 0.67 pixels, while the rigid-body translation test performed to validate the stereo-DIC system showed residual displacement errors within ± 0.1 mm with negligible strain. Under the halogen heating condition, IR measurements agreed with calibrated thermocouples with an RMSE below 1°C . In coupled experimental testing, measured temperature deviations were generally within 2°C , while the DIC and laser measurements provided a reference to assess the tip displacement.

Following spatiotemporal synchronisation, the full-field measurements showed a relationship between the imposed temperature gradient and structural deformation. The temperature and corresponding DIC z-displacement maps in Figure 2 reveal that the region closest to the halogen source reached approximately 65–70°C and exhibited comparatively larger out-of-plane displacement, while cooler regions showed lower displacement. The non-uniform deformation field indicated thermally induced bending or warping rather than simple uniform thermal expansion.

Temporal measurements further showed that the out-of-plane response did not vary monotonically with temperature. Although the temperature stabilised within a relatively narrow elevated range after initial heating, the out-of-plane displacement continued to fluctuate and change direction. For the 0.3 mm thick strip, a first-order estimate indicated that a through-thickness temperature difference of approximately 0.13 K could produce an out-of-plane displacement of about 0.5 mm, demonstrating the sensitivity of the slender specimen to small thermal gradients and their potential for thermoelastic-structural interaction under radiative heating [3]. In contrast, in-plane displacement developed more gradually, with the measured value of approximately 0.20 mm remaining close to the theoretical estimate of 0.15 mm. These observations demonstrate the value of simultaneous full-field measurements for interpreting coupled thermo-mechanical behaviour over discrete point measurements.

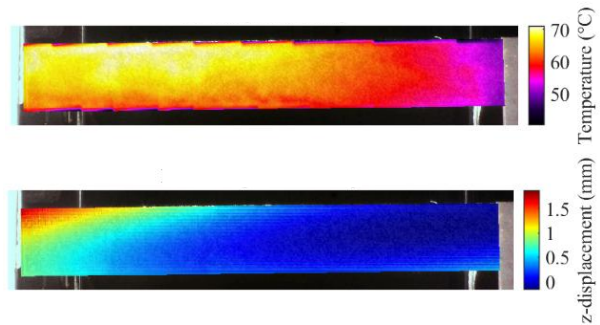


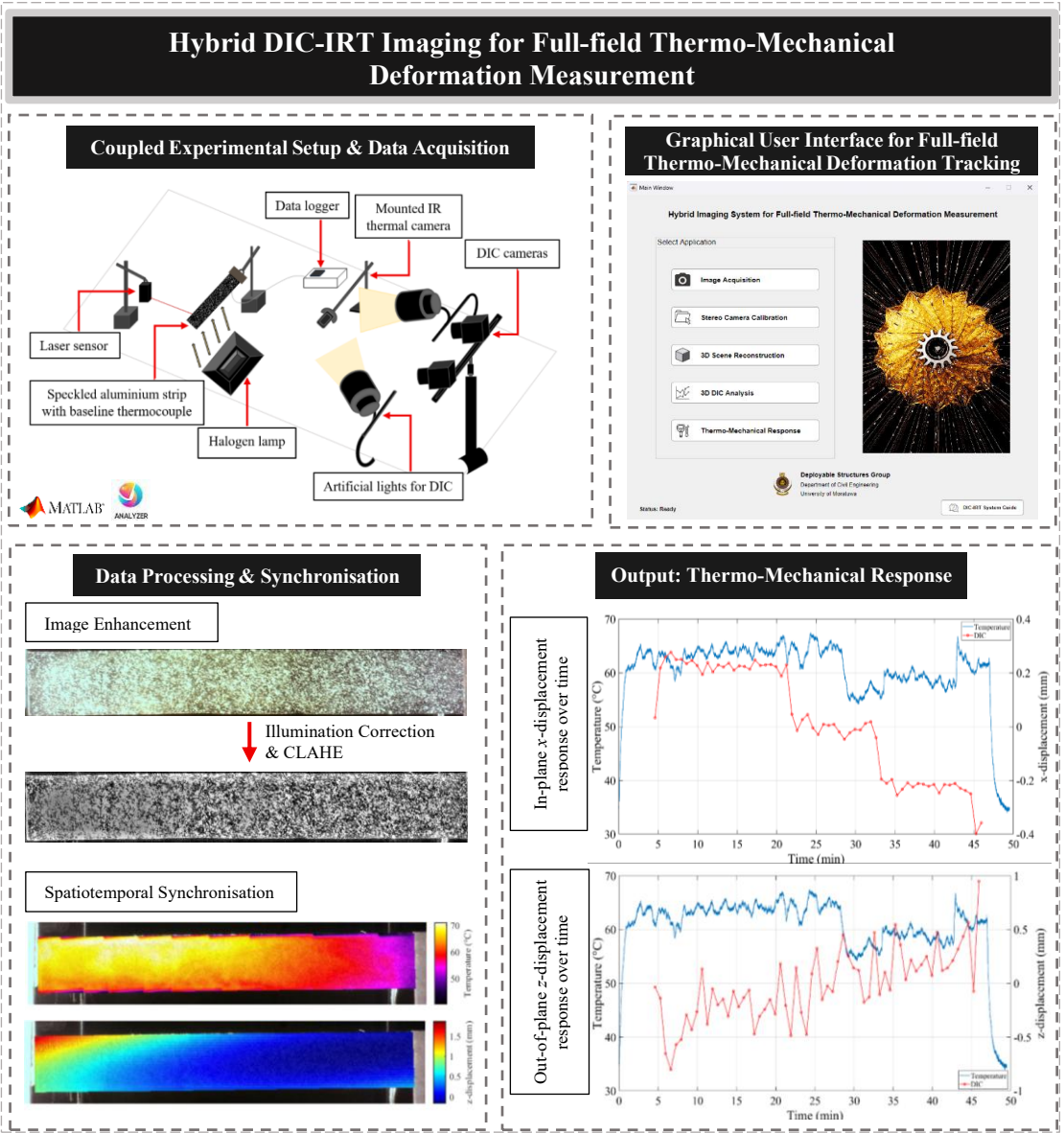
Figure 2: Full-field thermo-mechanical response at a representative time instant.

4. Conclusion

The study demonstrates a hybrid imaging system for synchronised full-field measurement of coupled thermo-mechanical responses under thermal loading, beyond the capability of contact instruments. By combining accessible hardware with custom processing, the system provides rich, spatially synchronised datasets useful for future structural assessment, model updating, digital twin applications and advanced experimental mechanics.

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STRENGTH RESTORATION OF DAPPED-END CONNECTIONS SUBJECTED TO INCREASED SHEAR SPAN-TO-DEPTH RATIOS

A.M.S.A. Amarasooriya^{1*}, M.G.D.D. Gamage¹, H.D. Yapa¹

¹ Department of Civil Engineering, Faculty of Engineering, University of Peradeniya, Sri Lanka

**Corresponding author: shashiniamaamarasooriya@gmail.com*

Abstract

Dapped-end (half-joint) connections are critical structural elements due to their vulnerability to failure. The sudden geometric reduction at the support creates a disturbed region (D-region) with severe stress concentrations and high localised shear, making the re-entrant corner particularly susceptible to cracking and shear failure. Precast concrete constructions typically use dapped-end beams to connect structural systems together and reduce overall depth for structural efficiency. Limited research evaluates the performance and failure mechanisms of these connections under increased shear span-to-effective depth (a/d) ratios. Higher a/d ratios can reduce shear capacity and pose challenges when adapting beams to longer shear spans. This study investigates the behaviour of reinforced concrete dapped-end beams across varying a/d ratios and evaluates retrofitting strategies to enhance structural performance. Using MIDAS FEA NX software, a 3D nonlinear finite element analysis is conducted to analyse material nonlinearity, crack propagation, and structural response, with a/d ratios ranging from 0.8 to 2.5 as the primary parameter. Horizontal carbon fibre wrap was used as the retrofitting method. The study revealed a reduction of shear capacity of the beams when the a/d ratio was increased. The retrofitting method significantly increased the shear capacity of each beam, by an average of 21% from the initial capacity.

Keywords: FEA analysis, Retrofitting, Shear strength, Carbon fibre wrap

1. Introduction

Reinforced concrete dapped-end beams are highly susceptible to sudden brittle shear failures at re-entrant corners ^[1] due to severe geometry-induced stress concentrations, as highlighted by real-world bridge collapses like the 2006 Concorde Overpass. The degree of strength, stiffness, and ductility enhancement is heavily governed by the beam's shear span-to-depth ratio (a/d), with beam concrete strength and detailing as other major decisive factors ^[2]. In-service dapped-end connections often suffer from detailing flaws, higher loads or degradation. Notably, a significant research gap remains regarding the shear capacity decreasing with the variation of a/d ratio. Traditional repair techniques such as steel plate jacketing and concrete enlargement add substantial dead weight and present installation challenges. Consequently, externally bonded wraps are preferred. This study presents a non-linear finite element parametric analysis evaluating control and horizontal carbon fibre wrap retrofitted dapped-end beams across varying a/d ratios to quantify failure mode transitions and demonstrate the structural viability of targeted retrofitting.

2. Methodology

After conducting a comprehensive literature review to identify dapped-end beam failure modes, shear span-to-depth ratio sensitivity, retrofitting schemes and non-linear finite element modelling, key geometric dimensions and parameters were established from benchmark literature. A non-linear three-dimensional finite element model was constructed, validated

against the experimental control specimen of Taher et al. [3] and subsequently utilised in a parametric study to evaluate structural performance across multiple varying a/d ratios. The beams were wrapped using carbon fibre to investigate the potential of retrofitting.

2.1 Finite Element Configuration

MIDAS FEA NX was utilised for complete 3D non-linear modelling to simulate internal stress distribution, crack initiation and post-cracking response. Concrete smeared-crack 3D solid elements were used for the concrete beam and 1D embedded truss elements were used for reinforcement meshing with a mesh size of 25 mm. The beam was modelled (shown in Figure 1) as simply supported, and load was applied as two-point loads symmetrically at 767 mm on either side of the mid-span centreline, at 45 kN each, giving a total of 90 kN.

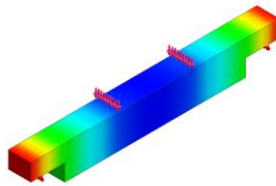


Figure 1: Beam dimensions and reinforcement configuration.

2.2 Model Validation

The finite element model was validated against the experimental results of Taher [3] comparing primarily load-deflection profiles and then ultimate shear capacities and crack propagation patterns at the re-entrant corner to ensure numerical accuracy. The a/d ratio of this control beam was 2.1. A 2% variation was observed between the numerical and experimental models, confirming the applicability of numerical methods in this study.

2.3 Beam Parametric Study

The dapped-end beam behaviour was evaluated for both non-retrofitted beams and horizontal carbon fibre wrap retrofitted beams, changing the a/d ratio within the range of 0.8 to 2.5 (0.8, 1, 1.2, 1.5, 1.8, 2.1, 2.3, 2.5). In this study, the effective depth (d) was constant while the shear span (a) varied. The retrofitting was conducted using 3 mm thick carbon fibre wrapping in the horizontal configuration, assuming ideal bonding between the beam and the wrap.

3. Results and Discussion

The study revealed the pivotal observation of shear capacity reduction of a dapped-end beam when a/d ratios increased, as Table 1 depicts. The a/d ratio vs shear capacity variation showed a valley variation of shear capacity of the dapped-end beams when the a/d ratio is increased from 0.8 to 2.5, with the lowest shear capacity for the beam with an a/d ratio of 2.3, exhibiting near-identical behaviour to Kani's valley, which explains the shear capacity variation for varying a/d ratios for typical beams. Figure 2 below shows the valley variation of a/d vs shear capacity for non-retrofitted beams and the figure highlights a substantial gain in shear performance in the retrofitted specimens compared to their non-retrofitted counterparts.

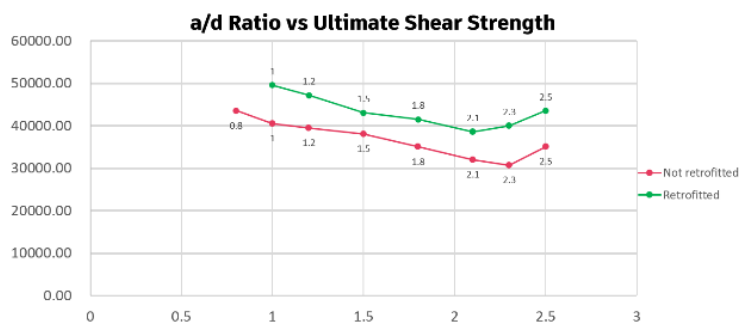


Figure 2: a/d vs ultimate shear strength of dapped-end beams for retrofitted and non-retrofitted beams.

Table 1: Shear capacity of beams with varying a/d ratios for retrofitted and non-retrofitted beams.

a/d ratio	Shear Capacity (N)		% Shear Capacity increase after retrofitting
	Non-Retrofitted	Retrofitted	
0.8	43504	-	-
1	40498	50000	22%
1.2	39498	47133	19%
1.5	38004	43000	13%
1.8	35000	41500	19%
2.1	32000	38500	20%
2.3	30737	40000	30%
2.5	35027	43500	24%

This study confirms that higher a/d ratios markedly degrade the shear capacity of dapped-end beams. Nevertheless, horizontal carbon fibre wrapping serves as an exceptionally robust retrofitting method, substantially restoring structural integrity. Crucially, the capacity enhancement was most pronounced in specimens prone to severe shear vulnerability, with the a/d = 2.3 configuration achieving the highest strength gain post-retrofitting.

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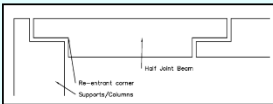
Strength Restoration of Dapped-End Connections Subjected to Increased a/d Ratios

Research Question

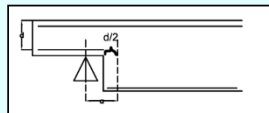
How does increasing a/d ratio affect the shear strength of dapped end connections?

Can CFRP retrofitting restore and enhance the shear capacity?

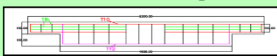
Dapped-End Beam Introduction



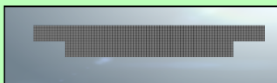
a/d definition for the study



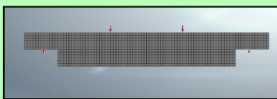
Beam FEA Modelling



Beam Concrete Mesh

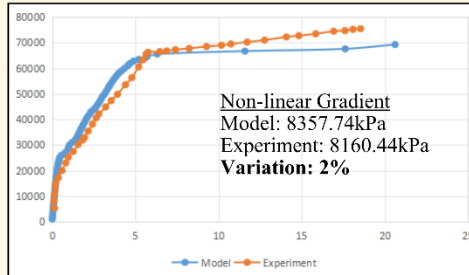


Beam Support and Load Conditions



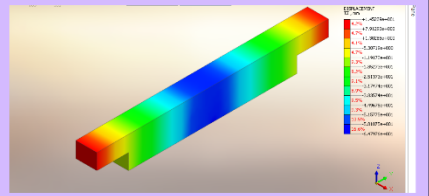
Model Validation

Against Taher (2005) control specimen experimental results



Parametric Study

Non-Retrofitted, Retrofitted beam behaviour against varying a/d ratios of 0.8 - 2.5

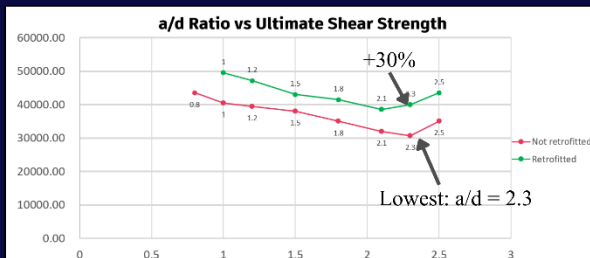


Retrofitting Method

Horizontal Carbon Fiber Wrap



Results



21%
Average Shear Capacity Gain after retrofitting

30%
Maximum Shear Capacity Gain for the weakest beam

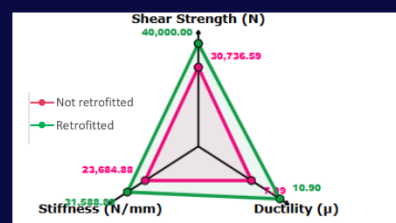


Figure: Shear Strength, Ductility, Stiffness variation for a/d=2.3 beam

All beams were enhanced in,

- shear strength
- ductility
- stiffness after retrofitting

INVESTIGATING THE STRUCTURAL ISSUES CAUSED BY TELECOMMUNICATION TOWERS CONSTRUCTED ON ROOFTOP SLABS

P. Shangari¹, H.G.H. Damruwan², K. Baskaran^{1*}

¹ Department of Civil Engineering, University of Moratuwa, Moratuwa, Sri Lanka

**Corresponding author: shangari.p.21@uom.lk*

Abstract

Rooftop installation of telecommunication towers on existing buildings has become a common strategy for expanding network coverage in dense urban areas of Sri Lanka. However, many existing structures were not originally designed to support the additional loads imposed by such installations, raising concerns regarding structural integrity and long-term durability. This study systematically investigates the structural and durability issues associated with rooftop telecommunication tower installations through field investigations across twelve sites, finite element modelling of a representative case study, and manual calculations per Eurocode standards. Field inspections revealed prevalent durability problems including water leakage, concrete spalling, and exposed reinforcement, though major structural failures were not observed. However, finite element analysis under ultimate limit state loading indicated that the host structure lacks adequate reserve capacity, with critical beams exhibiting insufficient flexural and shear reinforcement, meaning that visible condition alone is not a reliable indicator of ultimate safety. This research identifies systemic gaps in current installation practices and recommends amendments to strengthen structural verification, durability requirements, and regulatory enforcement for rooftop tower installations.

Keywords: Rooftop telecommunication towers, Structural assessment, Durability, Finite element analysis, Wind loading

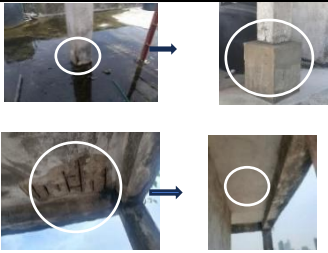
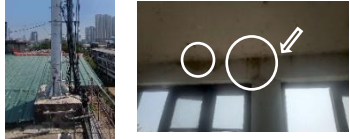
1. Introduction

Rooftop telecommunication tower installation has become a common solution to land scarcity in urban areas while providing building owners with supplementary income. However, many existing buildings were not originally designed to carry the additional static and dynamic loads imposed by these towers. Over time, these combined loads can cause excessive deflection, cracking, and overstressing of structural members, often leading to water leakage and accelerated material deterioration that may compromise building safety. Although the Telecommunication Regulatory Commission of Sri Lanka (TRCSL) established regulations in 2017 for the construction and maintenance of rooftop telecommunication towers, compliance with these requirements in practice remains inconsistent.

2. Methodology

The study combined qualitative field investigation with quantitative structural analysis, in three phases: literature and regulatory review, site investigation, and finite element modelling of a selected case study. Table 1 summarises four severe cases among the twelve site visits conducted. The four cases presented were purposively selected because they exhibited the most significant observable defects, specifically active structural cracking and water leakage issues.

Table 1: Summary of severe cases among the site visits conducted.

Site number	Building details and defects	Field observations	Site photos
Site 01	Storey – G+3 Tower height – 7 m	• Water ponding • Ageing of the structure • Cracks at the bottom of the column and concrete spalling were observed and rectified later.	
Site 02	Storey – G+4 Tower height – 7 m	• Water leaking issues and wet patches were identified inside the building, near the slab and beam connection.	
Site 03	Storey – G+4 Tower height – 9 m	• Longitudinal cracks were observed along the beam. • Wet patches were observed. • No waterproofing has been done on the roof slab.	
Site 04	Storey – G+2 Tower height – 24 m	• Severe water leakage and wet patches were observed at the slab soffit. • Waterproofing and appropriate draining of rainwater have not been provided.	

The summary of site visits indicated generally satisfactory structural performance across most locations. Most sites incorporated deliberate load transfer systems, such as separate base beam arrangements or thick concrete blocks, to effectively direct loads to host structure elements and prevent direct damage to the roof slab. Durability provisions, by contrast, were deficient at almost every site, including those with structurally sound arrangements. To critically evaluate structural integrity, a detailed analysis was conducted for a selected case study.

3. Analysis and Results

A detailed finite element analysis was conducted using SAP2000 for a 9 m monopole tower on a four-storey building. It was selected because it was the only accessible site exhibiting visible beam cracking beneath the tower together with water ingress and wet patches. The selection was purposive and is therefore treated as an indicative worst case rather than a generalisable sample. Dead and live loads were applied per Eurocode EN 1991. Wind loads were calculated following EN 1991-1-4:2005, using Section 7.9 for the circular pole and Section 7.6 for rectangular antennas. Eight wind directions were considered. Load combinations were formulated per Eurocode EN 1990, incorporating 33 ULS and 17 SLS combinations to assess structural integrity. The analysis results obtained are presented in Table 2.

Table 2: Results for modelling the case study.

Beam	Check	Condition	Required R/F (mm ²)	Provided R/F (mm ²)	Utilisation ratio = Demand / provided capacity	Status
Beam 01	Flexure (Sagging)	ULS	321	339	$321/339 = 0.947$ (<1)	Marginally adequate
Beam 01	Flexure (Hogging)	ULS	387	339	$387/339 = 1.142$ (>1)	Inadequate
Beam 02	Flexure (Sagging)	ULS	525	339	$525/339 = 1.549$ (>1)	Inadequate
Beam 02	Flexure (Sagging)	SLS	376	339	$376/339 = 1.109$ (>1)	Inadequate
Beam 01	Shear	ULS	R6 Mild Steel (275 MPa) @ 95 mm	Provided spacing is insufficient.	-	Shear links required
Beam 01	Shear	SLS	R6 Mild Steel (275 MPa) @ 130 mm	Spacing close to provided spacing of 120–150 mm	-	Sufficient

- Properties used - Beam 200×250 mm, concrete Grade 30 ($f_{ck} = 30$ MPa), steel S275 ($f_{yk} = 275$ MPa), 25 mm cover, 3T12 top and bottom bars, R6 links @ 120–150 mm.

4. Conclusion

- The provision of separate steel or concrete base beam systems effectively redirects tower loads to building columns, reducing stress concentrations in slabs and beams.
- The observed cracking in the case study was primarily attributable to durability deterioration and construction deficiencies rather than immediate structural overload, though the analysis confirms that the structure lacks adequate reserve capacity for future extreme loading events.
- The findings also highlight critical gaps in the current TRCSL regulatory framework. While guidelines mandate structural certification by a Chartered Civil Engineer, the analysis reveals ambiguity in practical compliance, as inadequate reinforcement was identified at several critical sections.
- The regulations do not adequately address long-term durability issues including waterproofing, drainage, and construction quality, which were widely observed across site visits and can progressively compromise host structures. To address these shortcomings, it is recommended that TRCSL guidelines be expanded to include mandatory maintenance reporting and detailed inspection requirements, enabling early detection of deterioration.

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INVESTIGATING THE STRUCTURAL ISSUES CAUSED BY TELECOMMUNICATION TOWERS CONSTRUCTED ON ROOF TOP SLABS

Background



Different types of towers installed

1. Self supporting monopole tower
2. Self supporting lattice tower
3. Pole with supporting struts
4. Guyed mast

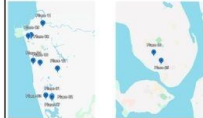
→ Expansion of network coverage ✓

→ Solution for land scarcity ✓

→ Income for building owners ✓

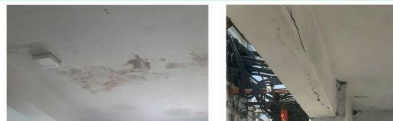
→ However, they compromise structural stability and durability performance of host structure.

Methodology



12 site visits done across Colombo and Batticaloa

- Cracks in beams
- Water leakages in beams and slabs
- No proper waterproof and water drainage provision.

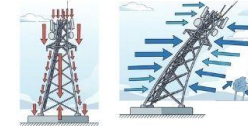
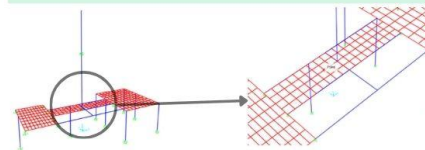


Finite element modelling was done for the selected case study to check the compliancy with the regulations in practice.

FE analysis

FE analysis done on SAP2000.

Eurocodes used for manual calculations



Static loading and Wind loading are applied

Analysis results shows that the host structure reinforcement is inadequate for ULS conditions

Conclusion

Adopt proper load transfer system

Durability issues are mostly observed and need to be considered before and after tower installation

Telecommunication Regulatory Commission Sri Lanka (TRCSL) guidelines should be adopted strictly and regular maintenance and inspection is required.

TRCSL guidelines should be amended to confirm the long term stability of host structures, provision of waterproofing and water drainage should be checked.

EXPERIMENTAL MECHANICAL CHARACTERISATION OF SELECTED SRI LANKAN HARDWOOD TIMBER SPECIES FOR LOCAL STRUCTURAL TIMBER DESIGN APPLICATIONS WITH REFERENCE TO EN 338

M.V.Y. De Silva¹, Kanishka Chandrathilaka^{1*}

¹ Department of Civil Engineering, University of Moratuwa, Sri Lanka

**Corresponding author: desilvamvy.21@uom.lk*

Abstract

Timber is a renewable structural material, but Sri Lankan design practice often relies on properties developed for foreign species and strength classes. This study established a preliminary local dataset for Hora, Jak, Mahogany and Teak and compared their behaviour with values commonly adopted from EN 338. Fifty-three small clear specimens were tested in four-point bending, tension parallel to grain, compression parallel to grain and compression perpendicular to grain. Moisture content and density were also measured. Clear differences occurred between species and loading directions. Teak had the highest density and bending stiffness, Hora the greatest bending strength, Mahogany the highest tensile strength, and Jak the highest moisture-normalised compression strength parallel to grain. Compression perpendicular to grain was far lower than longitudinal compression for all species tested in that mode, confirming the need for separate bearing and support zone checks. The measured mean properties showed different relationships with EN 338 benchmarks across the loading modes, indicating that a single reference class does not consistently represent all measured properties of these local hardwoods. The reported values are preliminary sample means rather than characteristic design values. The dataset supports the development of a nationally verified timber property database, although larger samples and full-size graded-member testing are required before formal strength classes can be proposed.

Keywords: Sustainable construction, Engineering materials, Eurocode 5, Anisotropic behaviour, Strength classification

1. Introduction

Timber is increasingly important in sustainable construction because it is renewable, relatively light and capable of storing carbon during service [1,2]. Sri Lankan hardwoods are widely used in roofs, floors, joinery, furniture and temporary works. However, structural calculations commonly depend on international handbooks and Eurocode-related values rather than on experimentally verified data for locally grown species.

Mechanical behaviour varies with species, density, moisture, grain direction and defects [1,2]. Direct use of European values may therefore underuse efficient local timber or overestimate a particular property. Because timber is orthotropic, bending, longitudinal tension and compression, and transverse bearing must be checked separately.

EN 408 defines mechanical test procedures and EN 338 provides strength classes used in Eurocode design [3,4]. Sri Lankan research has already highlighted the need for end-use-based classification [5]. This study characterises Hora, Jak, Mahogany and Teak, compares their measured behaviour with EN 338-related practice, and identifies local design implications. Formal class assignment is outside the scope because small clear specimens do not represent graded full-size populations.

2. Materials and Methods

Four commonly available hardwoods representing different density and strength ranges were tested. Small clear specimens were used to minimise large-defect effects. A total of 53 small clear specimens were tested: 20 in four-point bending, 12 in tension parallel to grain, 12 in compression parallel to grain, and 9 in compression perpendicular to grain, with direction defined relative to the grain. Table 1 summarises the arrangements and outputs, and Figure 1 shows the four test configurations.

Table 1: Experimental programme for mechanical characterisation.

Test	Specimen and loading arrangement	Coverage	Main output
Four-point bending	20 × 20 × 380 mm; 360 mm span	5 per species; 20 total	Strength and global modulus
Tension parallel to grain	10 × 20 mm critical section; along grain	3 per species; 12 tested	Tensile strength
Compression parallel to grain	20 × 20 × 120 mm; area 400 mm ²	3 per species; 12 total	Strength and elastic response
Compression perpendicular to grain	45 × 70 mm loaded area; height 90 mm	3 per species for Jak, Mahogany and Teak; 9 total; Hora not tested	Bearing strength and modulus
Moisture content and density	Masses and specimen volume	All four species	Moisture content and density

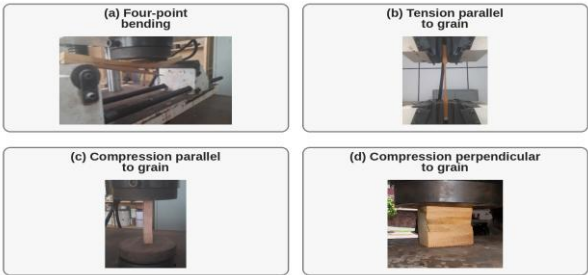


Figure 1: Experimental configurations used for the four mechanical loading modes.

Bending stiffness was obtained from the initial linear load-deflection region. Two tension specimens that failed at the grips were excluded from the strength analysis. No grip failures were present in the retained tension dataset. Compression parallel specimens used a 400 mm² area, while perpendicular specimens were loaded over 3150 mm² to represent support and contact-zone bearing.

Properties were calculated using EN 408-compatible expressions [3]. The oven-dry method provided moisture content, and density was estimated at 12 % moisture. Bending modulus and compression parallel strength were normalised to the same reference condition. EN 338 served only as a benchmark and was not used to assign classes [4]. The retained tension specimens showed comparatively brittle failure, while compression parallel to grain exhibited progressive fibre crushing and post-peak softening, and compression perpendicular to grain showed local crushing across the grain.

3. Results and Discussion

Mean moisture content during testing ranged from 15.1 % for Teak to 18.2 % for Hora. Estimated density at 12 % moisture ranged from 494 kg per cubic metre for Mahogany to 778 kg per cubic metre for Teak. The principal strength results are presented in Table 2. The data show that the four species cannot be treated as one uniform hardwood group.

Table 2: Experimental mean $\pm$ SD properties and EN 338 characteristic benchmarks.

Species / bending benchmark	Density at 12% (kg/m ³)	Bending strength (MPa)	Tension parallel (MPa)	Compression parallel at 12% (MPa)	Compression perpendicular (MPa)
Hora / D50	534	47.8 $\pm$ 10.0 / 50	18.6 $\pm$ 0.884 / 30	17.1 $\pm$ 0.742 / 30	Not tested / 6.2
Jak / D40	685	38.7 $\pm$ 4.88 / 40	32.6 $\pm$ 12.6 / 24	37.7 $\pm$ 7.75 / 27	12.8 $\pm$ 1.63 / 5.5
Mahogany / D30	494	30.4 $\pm$ 2.91 / 30	46.4 $\pm$ 0.884 / 18	26.0 $\pm$ 1.61 / 24	5.88 $\pm$ 0.601 / 5.3
Teak / D45	778	46.5 $\pm$ 10.3 / 45	41.8 $\pm$ 14.6 / 27	34.2 $\pm$ 11.9 / 29	14.7 $\pm$ 1.60 / 5.8

Values are experimental mean $\pm$ SD / EN 338 characteristic benchmark. Valid n: bending = 5/species; compression-parallel = 3/species; compression-perpendicular = 3 for Jak, Mahogany and Teak; tension = 2, 3, 2 and 3 for Hora, Jak, Mahogany and Teak after two grip-failure exclusions. D-classes are nearest bending-strength benchmarks only; no formal class assignment is implied.

Hora and Teak gave the highest bending strengths, 47.8 MPa and 46.5 MPa. Teak also had the greatest global bending modulus at 7.07 GPa. Rankings changed with loading mode: low-density Mahogany produced the highest tensile strength at 46.4 MPa, whereas Jak achieved the highest moisture-normalised compression-parallel strength at 37.7 MPa. Density alone therefore did not predict the full mechanical response.

Directionality was clearest in compression. Jak, Mahogany and Teak recorded perpendicular strengths of 12.8 MPa, 5.88 MPa and 14.7 MPa, respectively, compared with parallel strengths of 37.7 MPa, 26.0 MPa and 34.2 MPa. Supports and concentrated contact zones therefore require separate across-grain checks. Hora was not tested in compression perpendicular to grain because suitable material meeting the required specimen dimensions was not available within the experimental programme.

Comparison with the EN 338 benchmarks in Table 2 shows that similarity in bending strength does not imply corresponding agreement in tension or compression. The comparison is indicative only because the experimental results are sample means from small clear specimens, whereas EN 338 values are characteristic properties of structural timber; therefore, no formal strength-class assignment is proposed.

4. Design Implications and Conclusions

The results demonstrate strong species- and direction-dependent behaviour and support the need for locally verified timber properties rather than direct substitution of a single foreign strength class. The reported values are preliminary sample means and should not be treated as characteristic design values. Larger datasets using multiple source trees and full-size graded members, together with further investigation of perpendicular compression, shear, connections, load duration and moisture effects, are required before formal Sri Lankan strength classes can be proposed.

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RE-EVALUATING TIMBER STRUCTURES IN SRI LANKA: EXPERIMENTAL CHARACTERISATION OF SELECTED HARDWOODS

A corrected research flow for local structural timber design

1 RESEARCH GAP & OBJECTIVE

CURRENT PRACTICE (SRI LANKA)

Design based on European softwoods and EN 338 assumptions



European softwood (e.g., Spruce)

Generic EN 338 values not representative of local hardwoods

NEED FOR LOCAL SPECIES-SPECIFIC DATA



Sri Lankan hardwoods show wide variation in density and strength.

Local data required for safe, efficient design.

OBJECTIVE

- Experimentally characterise selected Sri Lankan hardwoods.
- Compare behaviour across loading modes, using EN 338 as a benchmark only.

Problem: Sri Lankan timber design often relies on foreign EN 338-related values rather than experimentally verified local hardwood data.

2 TIMBER MATERIAL SELECTION (SRI LANKA)

Hora

Dipterocarpus zeylanicus



Jak

Artocarpus heterophyllus



Mahogany

Swietenia macrophylla

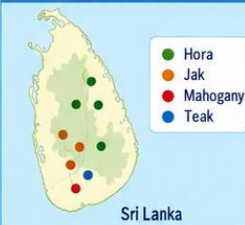


Teak

Tectona grandis



STUDY CONTEXT



DENSITY AT 12% MOISTURE

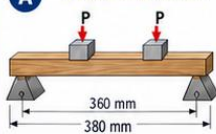
Species	Density (kg/m ³)
Hora	534
Jak	685
Mahogany	494
Teak	778

53 small clear specimens total

Mean moisture content during testing: 15.1% – 18.2%

3 MULTI-MODE MECHANICAL TESTING PROGRAM

A FOUR-POINT BENDING



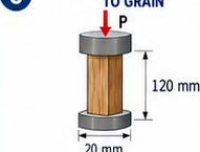
- Specimen: 20 × 20 × 380 mm
- Span: 360 mm
- Output: bending strength and global modulus ($f_{m,g}$, $E_{m,g}$)

B TENSION PARALLEL TO GRAIN



- Critical section: 10 × 20 mm
- Corrected critical area: 200 mm²
- Output: tensile strength ($f_{t,0}$)

C COMPRESSION PARALLEL TO GRAIN



- Specimen: 20 × 20 × 120 mm
- Area: 400 mm²
- Output: compression strength and elastic response ($f_{c,0}$)

D COMPRESSION PERPENDICULAR TO GRAIN

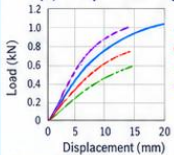


- Loaded area: 45 × 70 mm
- Height: 90 mm
- Loaded area = 3150 mm²
- Output: bearing/compression perpendicular strength and modulus ($f_{c,90}$)

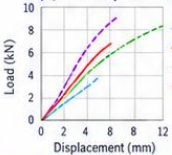
EN 408-compatible expressions used for property calculation.

4 KEY RESULTS: MEAN LOAD-DISPLACEMENT RESPONSES & REPRESENTATIVE MEAN VALUES

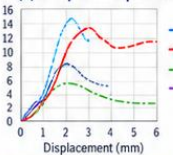
(a) four-point bending



(b) tension parallel to grain



(c) compression parallel to grain



(d) compression perpendicular to grain

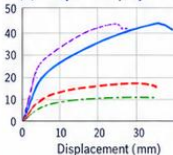


Figure 5 Mean load-displacement responses of selected Sri Lankan hardwood species under different loading modes: (a) four-point bending, (b) tension parallel to grain, (c) compression parallel to grain, and (d) compression perpendicular to grain.

Representative mean species-specific values (MPa)

Species	Bending strength f_m (MPa)	Global bending modulus $E_{m,g}$ (MPa)	Tension parallel $f_{t,0}$ (MPa)	Compression parallel at 12% $f_{c,0,12}$ (MPa)	Compression perpendicular $f_{c,90}$ (MPa)
Hora (H)	47.8	6289	18.6	17.1	Not tested
Jak (J)	38.7	5353	32.6	37.7	12.8
Mahogany (M)	30.4	4611	46.4	26.0	5.88
Teak (T)	46.5	7066	41.8	34.2	14.7

H – Hora J – Jak M – Mahogany T – Teak | NT – Not tested

SYNTHESIS FINDINGS

- Hora:** strongest in bending.
- Mahogany:** highest tensile strength despite low density.
- Jak:** highest moisture-normalised compression parallel strength.
- Teak:** highest density and bending stiffness.
- Compression perpendicular to grain is much lower than compression parallel to grain for all species tested.
- EN 338 is a benchmark only; species-specific local data are recommended.

BUCKLING BEHAVIOUR OF COLD-FORMED STEEL Z-SECTIONS UNDER AXIAL COMPRESSION AND BI-AXIAL BENDING

L.A.D.T. Senaratne¹, Kavindu Prabasha¹, Sumudu Herath^{1*}

¹ Department of Civil Engineering, University of Moratuwa, Moratuwa, Sri Lanka

**Corresponding author: sumuduh@uom.lk*

Abstract

Cold-formed steel (CFS) Z-sections are widely used as purlins, girts, and secondary framing members, yet their response becomes complex when axial compression acts together with bending about both principal axes. This study investigates the buckling capacity and failure behaviour of Z-section members under concentric and eccentric compression and evaluates the influence of member geometry and web perforations. Material properties were established from tensile coupon tests, after which four 500 mm non-perforated specimens were tested under axial, major-axis eccentric, minor-axis eccentric, and bi-axial loading. Finite element models were developed in ABAQUS and were validated against the experimental results. The validated model was then used to quantify the influence of member length, section thickness, and web opening diameter. Parametric analyses showed that increasing member length from 500 mm to 1500 mm reduced capacity by approximately 14% under pure compression and by 27% and 37% for bi-axial eccentricities of 20 mm by 20 mm and 40 mm by 40 mm, respectively; increasing section thickness from 1.96 mm to 3.00 mm enhanced capacity by approximately 76–82%, whereas a 40 mm web perforation reduced capacity by approximately 4–6%. The results demonstrate that eccentricity, slenderness, section thickness, and opening size are important parameters governing the stability of CFS Z-section beam-columns and provide a validated basis for further design-oriented studies.

Keywords: CFS, Eccentric loading, Finite element modelling, Thin-walled structures, Web perforations

1. Introduction

Cold-formed steel (CFS) members provide high strength-to-weight efficiency, rapid fabrication, and economical construction, leading to their extensive use in lightweight structural systems. Z-sections are widely used as purlins, girts, and secondary framing because they can be nested for transportation and efficiently lapped in continuous-span applications. Their asymmetric geometry places the principal axes and shear centre away from simple geometric reference lines, resulting in complex beam-column behaviour. In practice, axial forces are often accompanied by eccentricities that generate bending about one or both principal axes. Under these combined actions, local, distortional, and global instability modes may interact, thereby reducing the available resistance [1], [2].

Web perforations are also common in thin-walled members because they accommodate services and other construction requirements. Such openings reduce the effective web area and stiffness and introduce stress concentrations, with larger openings generally producing greater strength reductions [3]. Although previous studies have examined CFS beam-columns and Z-section behaviour, the combined influence of bi-axial eccentricity, member geometry, and web openings remains insufficiently characterised for practical Z-section members. Accordingly, the present study combines laboratory testing with validated finite element modelling to

quantify the influence of eccentricity, member length, section thickness, and the size of circular web perforations on buckling capacity and failure response.

2. Methodology

A commercially available lipped Z-section was investigated with a mean web depth of 101.55 mm, flange widths of 50.01 mm and 44.39 mm, lip lengths of 16.07 mm and 18.15 mm, and a thickness of 1.96 mm. Four non-perforated specimens, each 500 mm long, were tested. Three tensile coupons extracted from the flat web were tested in accordance with ISO 6892-1 [4], giving mean yield strength, ultimate tensile strength, and elastic modulus values of 589.3 MPa, 610.3 MPa, and 181 GPa, respectively. Each specimen was welded to 180 mm × 180 mm × 4 mm end plates and connected to a 20 mm thick drilled base plate. The compressive load was applied through the centroid of the base plate, while eccentricity was introduced by translating the specimen relative to the fixed loading point. This arrangement enabled the required eccentricities to be applied consistently. Nominally pinned end conditions were provided, and the experimental arrangement is shown in Figure 1.

Three-dimensional finite element models were developed in ABAQUS using S4R shell elements [5]. Measured material properties were incorporated, while reference points and multi-point constraints reproduced the experimental loading and boundary conditions. Linear eigenvalue buckling analysis was first performed to obtain characteristic instability modes. Geometric imperfections of $0.34t$, $0.66t$, and $L/500$, where t is the section thickness and L is the member length, were introduced for local, distortional, and global buckling, respectively. A mesh sensitivity study covering element sizes from 25 mm to 2.5 mm resulted in the selection of a 5 mm mesh. Nonlinear analyses were performed, and the models were validated against experimental ultimate loads, displacement responses, deformed shapes, and buckling modes.

Following validation, the effects of member length (500 mm–1500 mm), thickness (1.96 mm–3.00 mm), loading condition (pure compression and bi-axial eccentricities of 20 mm × 20 mm and 40 mm × 40 mm), and circular web perforations (20 mm and 40 mm diameter) were investigated. The investigated loading configurations and corresponding experimental and numerical results are summarised in Table 1.



Figure 1: Experimental test setup.

Table 1: Comparison of experimental and finite element results for the tested Z-section specimens.

Specimen	Loading condition	e_{major} (mm)	e_{minor} (mm)	P_{exp} (kN)	P_{FEM} (kN)	$P_{\text{FEM}}/P_{\text{exp}}$	Failure mode
NP-1	Pure compression	0	0	164.35	165.26	1.01	Local buckling
NP-2	Uniaxial bending	20	0	73.69	76.35	1.04	Local buckling
NP-3	Uniaxial bending	0	40	60.90	62.26	1.02	Local buckling
NP-4	Bi-axial bending	−31	15	43.20	45.96	1.06	Local buckling

Note: e_{major} and e_{minor} denote the load eccentricities corresponding to bending about the major and minor principal axes, respectively; P_{exp} and P_{FEM} are the experimental and finite element ultimate loads, respectively.

3. Results and Discussion

As summarised in Table 1, eccentric loading produced a pronounced reduction in load-carrying capacity. NP-1, subjected to pure compression, achieved the highest experimental ultimate load

of 164.35 kN, whereas NP-4, subjected to bi-axial bending, reached only 43.20 kN. The major- and minor-axis uniaxial bending cases reached 73.69 kN and 60.90 kN, respectively. This reduction is attributed to the additional bending moments and non-uniform stress distributions generated by load eccentricity. Local buckling governed all four specimens. The finite element predictions agreed well with the experimental results.

Increasing member length from 500 mm to 1500 mm reduced capacity from 165.26 kN to 142.60 kN under pure compression. For bi-axial eccentricities of 20 mm $\times$ 20 mm and 40 mm $\times$ 40 mm, capacity decreased from 59.61 kN to 43.58 kN and from 37.25 kN to 23.46 kN, respectively, reflecting the combined effects of slenderness and bending. Increasing thickness from 1.96 mm to 3.00 mm raised the capacities to 298.49 kN, 105.09 kN, and 67.67 kN, confirming its strong influence on buckling resistance.

Web perforations caused smaller but consistent capacity reductions. Under pure compression, capacity decreased from 165.26 kN for the non-perforated section to 163.78 kN and 158.63 kN for 20 mm and 40 mm openings, respectively. For the 20 mm $\times$ 20 mm eccentricity case, capacity decreased from 59.68 kN to 56.40 kN, while the 40 mm $\times$ 40 mm case decreased from 37.25 kN to 35.37 kN. These reductions result from loss of effective web area and stiffness and stress concentrations around the openings.

4. Conclusion

The study demonstrated that loading eccentricity, member length, section thickness, and web perforation size influence the buckling capacity of CFS Z-sections. Experimental capacity decreased from 164.35 kN under pure compression to 43.20 kN under bi-axial loading, a reduction of approximately 74%. The outcomes are summarised in Table 2.

Table 2: Summary of principal parametric findings.

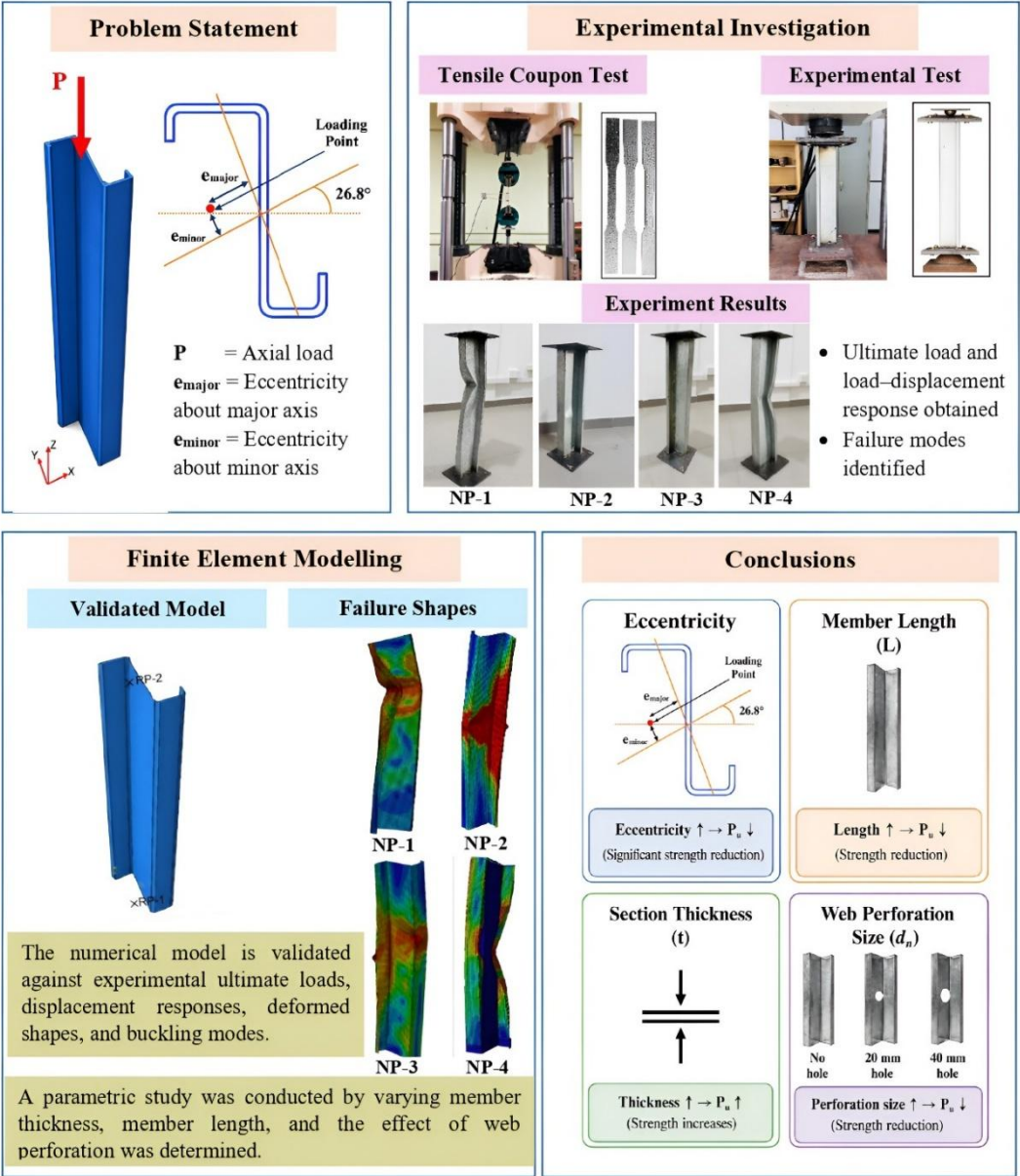
Parameter	Variation (mm)	Capacity improvement (+) or reduction (–) as per parameter variation		
		Pure compression	20 mm $\times$ 20 mm bi-axial eccentricity	40 mm $\times$ 40 mm bi-axial eccentricity
Member length (L)	500 - 1500	–14%	–27%	–37%
Section thickness (t)	1.96 - 3.00	+81%	+76%	+82%
Web perforation diameter (d)	0 - 40	–4%	–6%	–5%

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BUCKLING BEHAVIOUR OF COLD-FORMED STEEL Z-SECTIONS UNDER
AXIAL COMPRESSION AND BI-AXIAL BENDING

Objective: To investigate the buckling behaviour of cold-formed steel Z-section members under axial compression and biaxial bending, study the influence of key parameters, including member length, thickness, eccentricity, and the effect of web perforation



EXPERIMENTAL INVESTIGATION ON GEOMETRIC, PHYSICAL AND MECHANICAL PROPERTIES OF DENDROCALAMUS GIGANTEUS IN SRI LANKA

M.N. Thathsarani¹, P.L.N. Fernando¹, H.M.S.T. Herath^{1*}

¹ Department of Civil Engineering, University of Moratuwa, Moratuwa, Sri Lanka

*Corresponding author: sumuduh@uom.lk

Abstract

Bamboo is a fast-growing, low-carbon material with strong potential for sustainable construction, yet its structural use in Sri Lanka remains limited by the absence of species-specific engineering data. This study experimentally characterised the geometric, physical and mechanical properties of *Dendrocalamus giganteus* to assess its potential for structural applications. Mature culms harvested from Balangoda were evaluated using international bamboo grading and testing procedures. Geometric properties, including external diameter, wall thickness, taper, bow, ovality and internodal length, were measured on 188 culm sections. Basic density, linear mass, compression, tension and shear parallel to the fibres, and tension perpendicular to the fibres were also determined. Moisture contents of specimens in all mechanical test series ranged from 9 to 15 percent at testing. The mean external diameter and wall thickness were 157 mm and 10.8 mm, respectively, while mean basic density was approximately 662 kg/m³. Mean compressive, tensile and shear strengths parallel to the fibres were 46.85 MPa, 153.04 MPa and 8.47 MPa, respectively. Tensile strength perpendicular to the fibres was substantially lower at 1.75 MPa, indicating susceptibility to longitudinal splitting. The findings establish a first-stage engineering property dataset for the sampled material and support further structural assessment, while highlighting the need for additional tensile testing and careful detailing against splitting. Application requires consideration of sampling limitations and material variability, together with appropriate derivation of design values.

Keywords: Sustainable construction, Renewable materials, Structural grading, Orthotropic strength, Longitudinal splitting

1. Introduction

Bamboo is increasingly recognised as a renewable, low-embodied-carbon alternative to conventional construction materials, with rapid growth and a favourable strength-to-weight ratio [1], [2]. Sri Lanka contains several bamboo species, yet structural use remains limited because reliable species-specific engineering data are scarce. Bamboo is an orthotropic and naturally variable material whose properties depend on species, culm position, moisture condition and nodes; therefore, engineering properties should be established for the material and region of intended use [1]. *Dendrocalamus giganteus* (*D. giganteus*), commonly known as giant bamboo, is available in Sri Lanka and is characterised by large culm dimensions that may be advantageous for structural applications. However, a systematic engineering dataset for Sri Lankan *D. giganteus* has not been established. This study therefore characterises its geometric, physical and mechanical properties using recognised ISO procedures and provides a first-stage dataset for future structural assessment and design.

2. Materials and Methods

Mature culms of *D. giganteus*, free from visible defects, were harvested from the Balangoda region of Sri Lanka (approximately 6°39'N, 80°41'E; elevation 552 m; relative humidity 80–88%). Geometric properties, including external diameter, wall thickness, internodal length, bow, internal and external taper, and ovality, were determined at multiple positions along the culms in accordance with ISO 19624:2018 [3]. Physical properties (basic density and linear mass) and mechanical properties were determined in accordance with ISO 22157:2019 [4]. Moisture contents of specimens in all mechanical test series ranged from 9–15% at the time of testing. Compression parallel to the fibres was tested using short full-culm specimens; tension parallel to the fibres was tested using tabbed coupons cut from the culm wall; shear parallel to the fibres was evaluated using the prescribed shear specimen; and tension perpendicular to the fibres was assessed using the split-pin method. Each mechanical test series comprised 30 specimens with valid results. Table 1 summarises the geometric and physical properties.

Table 1: Summary of geometric and physical properties of *D. giganteus*.

Property	n	Mean	Min–Max
External diameter (mm)	188	157	107–194
Wall thickness (mm)	188	10.8	6.08–20.2
Diameter/thickness ratio	188	15.16	8.37–20.63
Internodal length (mm)	30	332	217–468
Basic density (kg/m ³)	30	662	386.3–871.8
Linear mass (kg/m)	30	4.10	0.71–8.59

3. Results and Discussion

The geometric survey confirmed that *D. giganteus* is a large-diameter species, with a mean external diameter of 157 mm and a mean wall thickness of 10.8 mm. The mean diameter-to-thickness ratio of 15.2 indicates a comparatively stocky culm section. Ovality (0.04), bow (1.86%) and taper (external 0.18%; internal 0.07%) were modest, indicating reasonably regular culm geometry. The mean basic density was approximately 662 kg/m³. These geometric and physical characteristics are comparable with values reported for structural bamboo species internationally [1], [2] and provide a useful basis for subsequent grading and structural assessment in accordance with ISO 22156:2021 [5].

Table 2: Summary of measured mechanical properties of *D. giganteus*.

Property	n	Mean (MPa)	COV
Compression fibres	30	46.85	0.168
Tension fibres	30	153.04	0.887
Shear fibres	30	8.47	0.250
Tension ⊥ fibres	30	1.75	0.302

n = number of specimens; COV = coefficient of variation; || = parallel; ⊥ = perpendicular.

Table 2 summarises the measured mechanical properties. The mean compressive strength parallel to the fibres was 46.85 MPa, while the mean tensile strength parallel to the fibres was 153.04 MPa, demonstrating the strong fibre-parallel response characteristic of structural bamboo [1], [2]. The mean shear strength parallel to the fibres was 8.47 MPa. In contrast, the mean tensile strength perpendicular to the fibres was 1.75 MPa, highlighting the susceptibility of the culm wall to longitudinal splitting under transverse loading and the importance of appropriate connection detailing.

3.1 Limitations and Practical Application

The study is limited to mature, visibly defect-free culms from Balangoda and 30 specimens per mechanical test series. Results should therefore not be generalised to all Sri Lankan *D. giganteus* or to different moisture conditions. The high variability in fibre-parallel tensile strength (COV = 0.887) also warrants additional testing. For construction, these results can inform preliminary material assessment and grading studies; the mean strengths should not be used directly as design values. Structural application requires appropriate grading, derivation of characteristic and design values under ISO 22156:2021 [5], and verification of member and connection performance, particularly against splitting.

4. Conclusions

This study establishes a first-stage geometric, physical and mechanical property database for Sri Lankan *Dendrocalamus giganteus*. The sampled culms exhibited large diameters, moderate wall thickness, favourable basic density and strong fibre-parallel performance. Low transverse tensile strength highlights longitudinal splitting as a critical consideration for connections and concentrated loads. The findings support further structural assessment while emphasising material variability and the need for grading and structural verification. They apply to the sampled population and test conditions.

Acknowledgements

The assistance of UNA GAMA (Pvt) Ltd with bamboo sample collection and preservation for this study is sincerely appreciated.

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EXPERIMENTAL INVESTIGATION

Geometric, physical and mechanical properties

of *Dendrocalamus giganteus* in Sri Lanka

Locally sourced bamboo • ISO-based characterization

01 MATERIAL & EXPERIMENTAL PROGRAM



Mature bamboo culms



Test specimen

BALANGODA, SRI LANKA

188

culm sections

for geometric characterization

30

specimens per

mechanical test series

Mature, defect-free culms

GEOMETRIC

Dimensions and form

ISO 19624:2018

PHYSICAL

Density and linear mass

ISO 22157:2019

MECHANICAL

Compression, tension, shear

ISO 22157:2019

Moisture content at testing: 9–15% across all mechanical test series

02 MEAN GEOMETRIC & PHYSICAL PROPERTIES

157

mm

External diameter

10.8

mm

Wall thickness

662

kg/m³

Basic density

03 MEAN MECHANICAL STRENGTH

Test / fiber direction		MPa	COV
Tension / parallel		153.04	0.887
Compression / parallel		46.85	0.168
Shear / parallel		8.47	0.250
Tension / perpendicular		1.75	0.302
COV: coefficient of variation		0	160 MPa

Low transverse strength highlights splitting risk in connections.

Average strengths are not design values; grading and structural verification are required before construction use.

RESIDUAL COMPRESSIVE PERFORMANCE OF LOW-CARBON MASONRY UNITS AFTER A STANDARD SINGLE-FACE FIRE

Prof. (Mrs.) Chintha Jayasinghe¹, Dr. Indunil Erandi², Dehipitiya.N.N^{1*}

¹ Department of Civil Engineering University of Moratuwa, Moratuwa, Sri Lanka

² Department of Civil Engineering University of Moratuwa, Moratuwa, Sri Lanka

**Corresponding author: dehipitiyann.21@uom.lk*

Abstract

Low-embodied-energy masonry such as CSEB, AAC and EPS blocks is displacing fired clay and dense cement units in tropical construction, yet what remains of these units after a building fire is poorly quantified. Existing data come almost entirely from furnaces that heat every face uniformly, unlike a wall exposed on one side only. This study compared four traditional and four alternative unit types under a gas-fired exposure tracking the ISO 834 standard curve to a peak exposed-face temperature of 600 degrees Celsius. Specimens were oven-dried to constant mass, insulated on every face except one to enforce one-dimensional heat flow, cooled in the furnace and then loaded to failure in compression. Fired clay gained capacity, reaching 138 percent of its unheated strength through secondary sintering, while every other unit lost between 11 and 24 percent. Retention followed continuity of the cross-section rather than material category, hollow units losing about twice as much as their solid counterparts. Three of the four alternatives fell below the minimum strengths of the relevant Sri Lanka Standards, showing that selection on embodied energy grounds must be paired with a post-fire capacity check.

Keywords: Sustainable construction, Embodied energy, Thermal degradation, Autoclaved aerated concrete, Compressed stabilised earth blocks

1. Introduction

Masonry carries most of the vertical load in low-rise construction across Sri Lanka and the wider tropics, and the units used for it are changing. Fired clay bricks are kiln-fired and dense cement blocks consume large volumes of ordinary Portland cement, so both carry high embodied carbon. Compressed stabilised earth blocks (CSEB), autoclaved aerated concrete (AAC) and expanded polystyrene (EPS) cored composite blocks are displacing them because they are unfired, use less raw material, or cut operational cooling loads. These alternatives are specified almost entirely on energy grounds, and what remains of them after a compartment fire is rarely part of that decision.

The omission matters, because carbon saved at construction is given back if a fire-damaged wall is demolished rather than repaired. Published residual data for these materials are thin, and almost all of them come from electric muffle furnaces that heat every face uniformly [1]. A wall in a real fire is heated on one face only, so a one-dimensional gradient develops and the cooler side retains capacity that uniform heating destroys; boundary conditions of this kind change the response of block masonry substantially [2], [3], and comparative evidence for lightweight and earth-based units is scarce [4]. This study quantifies the residual compressive strength, the retention and the post-fire code compliance of four traditional and four low-carbon typologies after single-face exposure to the ISO 834-1 curve at an exposed-face temperature of 600 °C.

2. Materials and Methods

Eight unit types were tested: fired clay brick, solid cement block, hollow cement block and a grade M4 mortar cube in the traditional group, and solid CSEB, hollow CSEB, AAC block and EPS-cored composite block in the low-carbon group. Dimensions were taken to BS EN 772-16, net cross-sectional areas were computed for the hollow and cored units, and dry density followed BS EN 772-13. Every specimen was oven-dried at 105 to 115 °C to BS EN 772-10 until successive masses differed by less than 0.2 %, then cooled to 25 °C in sealed containers. This zero-moisture baseline removes steam-driven spalling as a variable, so that any loss of strength is attributable to thermal degradation of the matrix rather than to pore pressure.

A gas-fired furnace was programmed to the ISO 834-1 time–temperature curve. Only one face of each unit was exposed; the remaining faces were wrapped in 50 mm ceramic-fibre blanket to approximate an adiabatic boundary, following BS EN 1363-1, so that heat flowed along a single axis (Figure 1). Six K-type thermocouples, three per face, recorded the gradient. Exposure continued to a peak exposed-face temperature of 600 °C, held for a 30-minute soak, after which specimens cooled in the furnace, were re-measured, capped and loaded to failure to BS EN 772-1 against unheated controls of every typology (replicate sample size n = 3 per exposure condition and unit type, giving a total of N = 48 specimens tested).

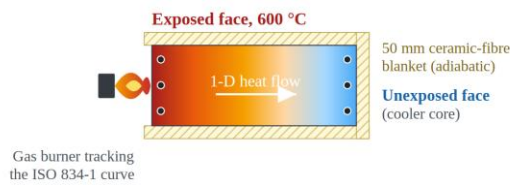


Figure 1: Single-face exposure arrangement enforcing one-dimensional heat flow.

3. Results and Discussion

Table 1: Ambient and residual compressive strength after single-face exposure to 600 °C.

Masonry unit	Dry density (kg/m³)	Ambient strength (MPa)	Residual strength (MPa)	Retention	Meets SLS minimum?
Clay brick	1757	11.08	15.28	1.38	Yes (2.8)
Cement solid	2111	9.75	8.70	0.89	Yes (2.5)
Cement hollow	2216	8.39	6.82	0.81	Yes (2.5)
Mortar M4	2150	12.46	9.77	0.78	Yes (4.0)
CSEB solid	1878	4.50	3.90	0.87	Yes, Grade II (2.8)
CSEB hollow	1680	4.64	3.59	0.77	No (4.0)
AAC block	608	0.97	0.85	0.88	No (1.2)
EPS core block	787	1.24	0.94	0.76	No (1.2)

Values in parentheses are the applicable SLS minimum strengths in MPa. Traditional units are listed first.

Retention was not organised by category (Figure 2). Fired clay alone gained capacity, rising to 1.38 times its baseline as secondary sintering continued at the exposed face, though with a shift to brittle, sudden failure. Every other unit lost 11 to 24 % of ambient capacity.

The controlling variable was continuity of the cross-section rather than embodied carbon. In both groups the hollow unit lost roughly twice as much as its solid counterpart: 19 % against 11 % for cement and 23 % against 13 % for CSEB. Voids drive heat through thin webs, and differential expansion between the hot face-shell and the restrained cooler webs produces shear cracking rather than uniform degradation.

For the low-carbon group the outcome is governed by absolute strength rather than retention. AAC retained 88 %, better than the hollow cement block, but its residual 0.85 MPa sits below the 1.2 MPa minimum for single-storey load-bearing use, as does the 0.94 MPa left in the EPS-cored unit. Solid CSEB, at 3.90 MPa, satisfies Grade II of SLS 1382-1 [5] but not Grade I, and hollow CSEB meets neither: one of four alternatives remains compliant after exposure, against four of four traditional units.

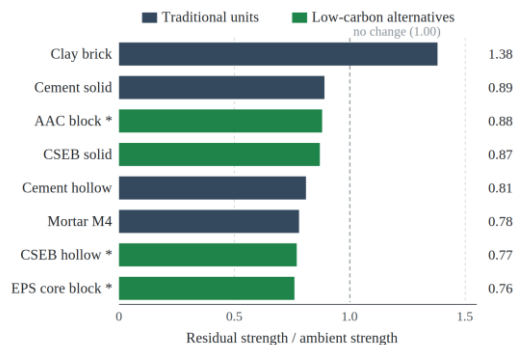


Figure 2: Strength retained after exposure. * residual strength below the applicable SLS minimum.

4. Conclusions

Under single-face ISO 834 exposure to 600 °C, fired clay gained strength while every other unit lost 11 to 24 % of ambient capacity. Retention was governed by section continuity, hollow units losing about twice as much as equivalent solid units in both the cement and the CSEB families. Three of the four low-carbon alternatives fell below the minimum strengths of the relevant Sri Lanka Standards, while solid CSEB retained Grade II compliance. Low-carbon units need not be avoided, but their fire case should be made at design stage: solid rather than hollow variants where a wall is load-bearing or fire-separating, aerated and cored units confined to non-load-bearing insulating duties, and a residual capacity check written into post-fire assessment rather than inferred from the ambient rating.

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Residual compressive performance of low-carbon masonry units after a standard single-face fire

Eight unit types, ISO 834-1 exposure to 600 °C on one face only, tested in residual compression

1 . UNITS COMPARED

Traditional (high embodied energy)

Clay brick

Cement solid

Cement hollow

Mortar M4

Low-carbon alternatives

CSEB solid

CSEB hollow

AAC block

EPS core block

2 . SINGLE-FACE ISO 834 EXPOSURE

Exposed face, 600 °C

50 mm ceramic-fibre blanket

Unexposed face

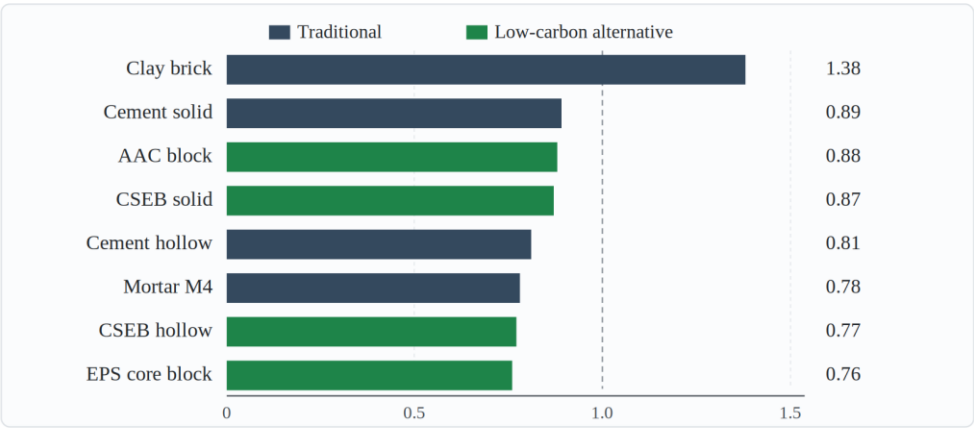
1-D heat flow

Gas burner

K-type

- One face exposed, every other face insulated
- ISO 834-1 curve to 600 °C, then a 30 min soak
- Oven-dried to 0 % moisture to exclude steam spalling
- Furnace-cooled, capped, loaded to failure

3 . STRENGTH RETAINED AFTER 600 °C



Traditional units
4 of 4 still meet the SLS minimum strength

Low-carbon alternatives
only 1 of 4 still meets the SLS minimum strength

Retention follows section continuity, not embodied carbon: hollow units lose about twice as much capacity as their solid counterparts.

Compliance assessed against SLS 39, SLS 855 Part 1 and SLS 1382-1.

UTILISATION OF GLASS WASTE AS A REPLACEMENT FOR NATURAL SAND IN MORTAR

C. Jayasinghe¹, I.E. Ariyaratne¹, H.R. Samaranayake^{1*}

¹ Department of Civil Engineering, University of Moratuwa, Moratuwa, Sri Lanka

**Corresponding author: hrsravishan@gmail.com*

Abstract

The depletion of natural river sand and the accumulation of non-biodegradable waste glass create resource and environmental challenges for construction. This study evaluated crushed waste glass as a partial replacement for natural river sand in one to five cement to fine aggregate masonry mortar. Six glass contents from zero to fifty percent by mass of the sand fraction were tested at a constant water-cement ratio of 0.60. Aggregate grading, flow table workability, dry bulk density, seven- and twenty-eight-day compressive and flexural strengths, and brick mortar bed joint shear performance were assessed using relevant European standards. The twenty percent mix achieved 174.50 mm flow, 2277.23 kg/m³ dry density, 10.52 MPa compressive strength and 1.87 MPa flexural strength at twenty-eight days. Relative to the control, compressive and flexural strengths increased by 42.33 and 7.70 percent, respectively. Bed joint shear strength was also slightly higher at all three precompression levels, while the initial shear strength intercept remained essentially unchanged. Considering acceptable workability, the highest measured strengths, a small density reduction and one fifth sand substitution, twenty percent was identified as the optimum level within the tested range. Long-term durability, especially alkali-silica reaction, and local processing cost require further assessment before field adoption.

Keywords: Circular economy, Workability, Compressive strength, Bed joint shear

1. Introduction

Natural river sand is widely used in masonry mortar, but excessive extraction can degrade riverbeds, destabilise banks and disturb habitats. Waste glass is durable and non-biodegradable, so converting it into fine aggregate can simultaneously reduce virgin sand demand and divert glass from disposal. Previous mortar studies confirm that waste glass can function as a sand substitute when its particle size and replacement level are controlled [1], [2].

Glass differs from river sand in particle shape, surface condition and water absorption, and its amorphous silica also raises an alkali-silica reaction concern that must be considered separately from short-term strength [3]. Fine glass mortar performance is strongly dependent on grading and particle geometry [4], while broader reviews identify waste glass reuse as a circular economy route for cement-based materials [5]. Evidence remains limited for ordinary one to five masonry mortar under local material conditions, particularly when mortar properties and brick mortar bed joint behaviour are considered together. The objective was therefore to identify a practical glass replacement level using workability, density, compressive strength, flexural strength and masonry shear performance.

2. Materials and Methods

Ordinary Portland cement, natural river sand, cleaned crushed waste glass, potable water and engineering clay bricks were used. A nominal one to five cement to fine aggregate masonry proportion was selected because it is a familiar proportion for local brickwork. For laboratory batching, the proportion was converted to masses, and glass replaced the sand fraction by mass. The water-cement ratio was fixed at 0.60 for all mixes so that changes in performance could be attributed to glass replacement rather than changes in water content. Six mixes were

prepared at 0, 10, 20, 30, 40 and 50 percent replacement and are designated WG0 to WG50; the WG notation is used to avoid confusion with concrete strength grade labels.

Sieve analysis was performed on 500 g dry samples using 4.75, 2.36, 1.18, 0.60, 0.30 and 0.15 mm sieves. Figure 1 compares the measured particle size distributions. The glass had lower percentages passing than the river sand from 2.36 to 0.15 mm, indicating a somewhat coarser grading, while both materials followed the adopted fine aggregate grading envelope. Aggregate specific gravity and absorption were not independently measured, so no unverified values are reported.

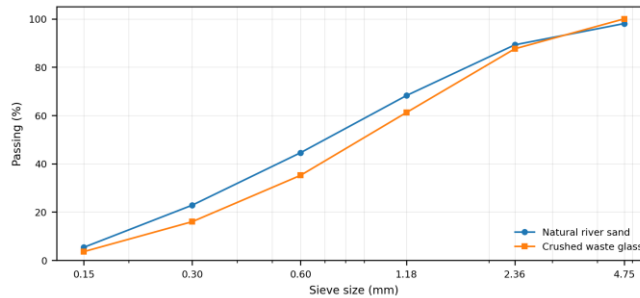


Figure 1: Particle size distribution of natural river sand and crushed waste glass.

Table 1: Test programme, standards and replication.

Property	Standard	Replication
Flow table workability	EN 1015-3	1 determination per mix (2 diameters)
Dry bulk density	EN 1015-10	3 specimens per mix
Compressive strength	EN 1015-11	3 cubes per mix at 7 and 28 days
Flexural strength	EN 1015-11	3 prisms per mix at 7 and 28 days
Bed joint initial shear	EN 1052-3	3 triplets per stress level for WG0 and WG20

3. Results and Discussion

The flow diameter remained within the adopted 165–185 mm target for every mix: 178.50, 175.00, 174.50, 170.00, 169.50 and 171.50 mm for WG0 to WG50, respectively. Dry bulk density decreased from 2335.29 kg/m³ for WG0 to 2277.23 kg/m³ for WG20 and 1993.00 kg/m³ for WG50. The density reduction at WG20 was only 2.49 percent, whereas larger reductions occurred above 30 percent replacement.

Compressive strength increased to a maximum at WG20 and then decreased. At 28 days, WG0, WG10, WG20, WG30, WG40 and WG50 achieved 7.39, 9.80, 10.52, 8.91, 7.91 and 7.74 MPa, respectively. Thus, WG20 was 42.33 percent higher than the control. The 28-day flexural strength followed the same optimum: 1.73 MPa for WG0 and 1.87 MPa for WG20, an increase of 7.70 percent, while WG40 and WG50 fell below the control. The study did not measure pore structure, interfacial transition zone characteristics or microcracking; therefore, the post-WG20 strength decline is reported as an experimental trend rather than assigned to a specific mechanism.

WG20 was selected for masonry validation only after the mortar screening stage because it combined acceptable workability, the highest 7- and 28-day compressive strengths, the highest 28-day flexural strength and only a small density reduction. This staged selection provided a

clear basis for limiting the more resource-intensive triplet testing to the control and the best-performing glass mix. Figure 2 summarises the compressive strength trend and the subsequent bed joint shear response.

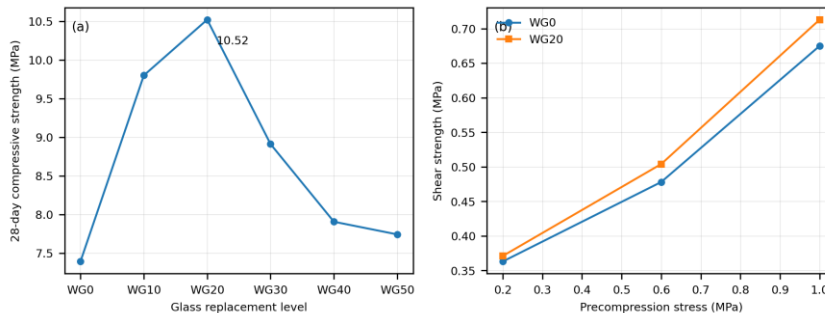


Figure 2: (a) 28-day compressive strength and (b) bed joint shear response of WG0 and WG20.

At precompression stresses of 0.20, 0.60 and 1.00 MPa, WG20 recorded shear strengths of 0.37, 0.50 and 0.71 MPa, compared with 0.36, 0.48 and 0.68 MPa for WG0. Linear regression gave initial shear strength intercepts of 0.273 MPa for WG20 and 0.272 MPa for WG0, while the friction coefficient increased from 0.390 to 0.427. The result indicates that the selected glass mortar did not reduce bed joint shear performance within the tested conditions.

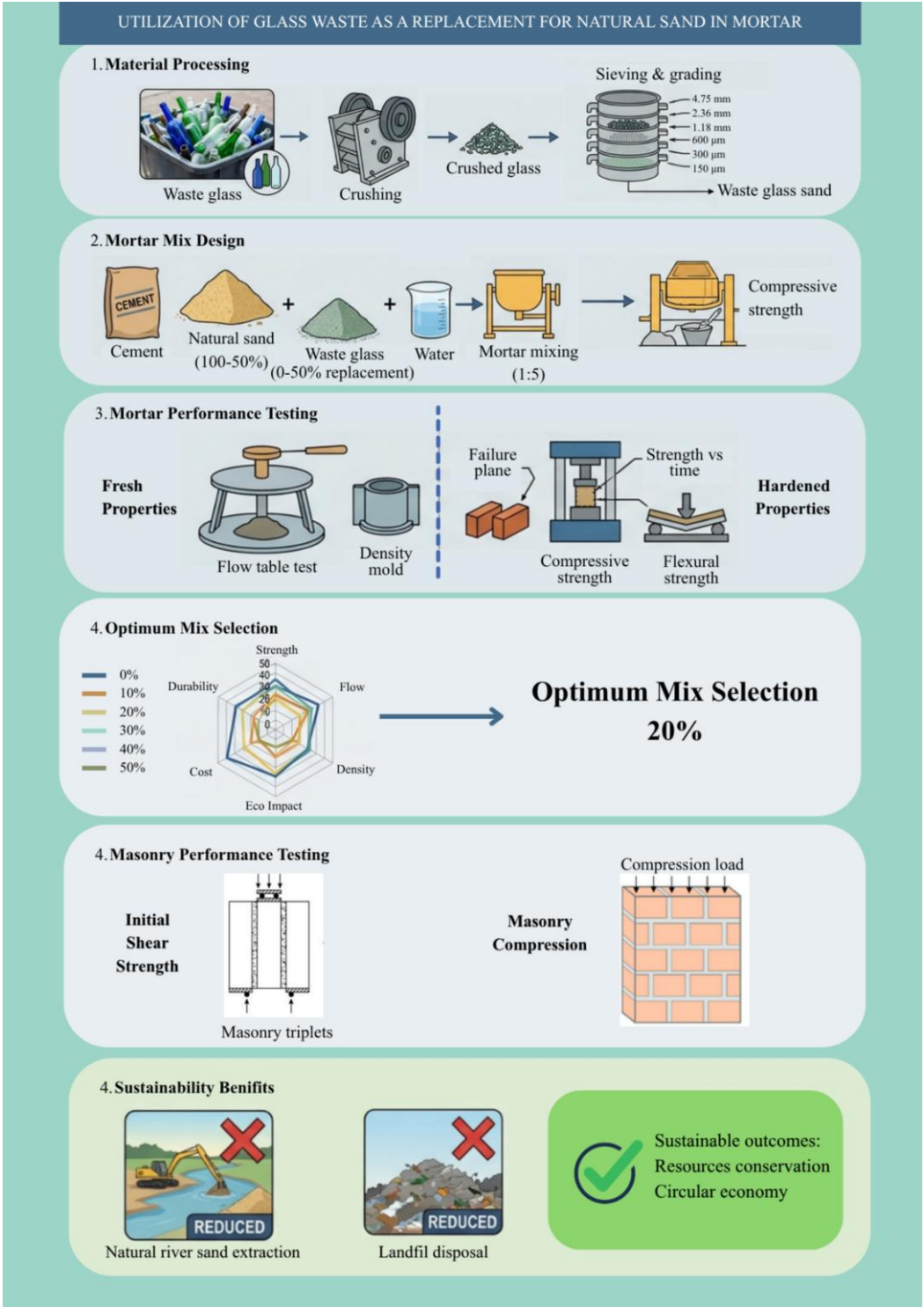
Durability was not experimentally evaluated, so alkali-silica reaction resistance cannot be concluded; dedicated expansion and exposure testing is required before routine use [3]. Practical use also requires consistent glass collection, sorting, cleaning, crushing and grading. These steps add transport and processing costs; because no cost analysis was undertaken, local economic feasibility remains to be verified.

4. Conclusions and Practical Implications

Within the tested one to five-masonry mortar system, 20 percent waste glass replacement provided the most balanced performance. WG20 remained workable at 174.50 mm flow, had only a 2.49 percent reduction in dry density, and achieved the highest 28-day compressive and flexural strengths of 10.52 and 1.87 MPa. It also matched or slightly exceeded the control in bed joint shear resistance. The result supports controlled partial replacement of natural river sand with processed waste glass, but the 20 percent value should be treated as the optimum for this material set and test programme rather than as a universal replacement level. Long-term ASR-related durability, moisture exposure, field workmanship and local processing economics should be verified through further testing and pilot masonry trials before large-scale adoption.

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EVALUATION OF FIRE RESISTANCE OF OPTIMISED LC3 MORTAR WITH ALKALI ACTIVATED GROUND GRANULATED BLAST FURNACE SLAG

U. Thulajah^{1*}, B.M.P.M. Balasooriya¹, T.G.P.L. Weerasinghe¹

¹ Department of Civil Engineering, University of Moratuwa, Sri Lanka

**Corresponding author: thulajahu23@gmail.com*

Abstract

Limestone Calcined Clay Cement (LC3) offers 50% clinker replacement with 30–40% lower CO₂ emissions than ordinary Portland cement (OPC), yet suffers from inferior fire resistance and excessive superplasticiser demand. Prior optimisation via Response Surface Methodology replaced half the calcined clay with ground granulated blast furnace slag (GGBFS), yielding optimal mixes OM1 (no alkali activation), OM1Na (1.2% Na₂SO₄-activated), and OM1Ca (Ca(OH)₂-activated). This study evaluates their high-temperature fire resistance. Mortar specimens were exposed to 200, 400, 600, and 800°C at 5°C/min with a 2-hour soak. At 200°C, OM1 retained 84.4% compressive strength while OM1Na and OM1Ca retained only 32.7% to 40.1%. Alkali-activated mixes spalled explosively at 400°C, whereas OPC never spalled. Geometry critically influenced survival: almost all optimised mix cubes exploded at 600°C, while prisms survived. At 800°C, thermal spalling and non-binding gehlenite formation caused collapse. The densified pore structure enhancing ambient durability paradoxically traps vapour pressure, triggering catastrophic failure. These optimised LC3 mortars are unsuitable for structural fire-safety applications without further modification.

Keywords: Cement, Fire resistance, Alkali activation, GGBFS, LC3

1. Introduction

LC3, comprising 30% calcined clay, 15% limestone, and 5% gypsum, achieves 50% clinker replacement with 30–40% lower CO₂ emissions than ordinary Portland cement (OPC) [1]. However, its adoption is constrained by excessive superplasticiser demand and inferior fire performance. Thermal degradation of calcined clay and limestone causes strength loss: portlandite dehydrates at 400–500°C and limestone decarbonates above 600°C, forming non-binding phases [2]. Internal vapour pressure from trapped moisture induces spalling [3]. Recent studies have characterised LC3's fire vulnerability, with LC3 concrete exhibiting 11.06% and 1.73% lower average residual compressive strength than OPC and PPC, respectively [4]. Substituting GGBFS improves fire resistance in cementitious systems [5]. A preceding study using response surface methodology (RSM) with D-optimal design partially replaced calcined clay with GGBFS, producing OM1 (no alkali activation), OM1Na (1.2% Na₂SO₄ activation), and OM1Ca (Ca(OH)₂ activation), achieving 28% higher 28-day strength, 30% lower superplasticiser demand, and 43% improved setting time over LC3. However, the fire resistance of these optimised mixes remains unexplored. This study evaluates their high-temperature performance through residual strength, mass loss, and spalling behaviour.

2. Methodology

Five mortar mixes were developed at a 1:2.75:0.6 binder:sand:water ratio: OPC (reference), plain LC3, OM1 (LC3+GGBFS, non-activated), OM1Na (LC3+GGBFS+1.2% Na₂SO₄), and OM1Ca (LC3+GGBFS+0.6% Ca(OH)₂). Prisms (40×40×160 mm) and cubes (70.7 mm) were cast, cured for 28 days, and air-dried for 24 hours. Samples were heated at 5°C/min to 200,

400, 600, and 800°C, soaked for 2 hours, and slow-cooled. Assessments included spalling, mass loss, residual compressive strength, and residual flexural strength (three-point loading).

3. Results and Discussion

3.1 Compressive and Flexural Strength

Charts present residual compressive and flexural strengths normalised to ambient (30°C = 100%). Zeros indicate no specimen survived due to spalling, not zero residual strength.

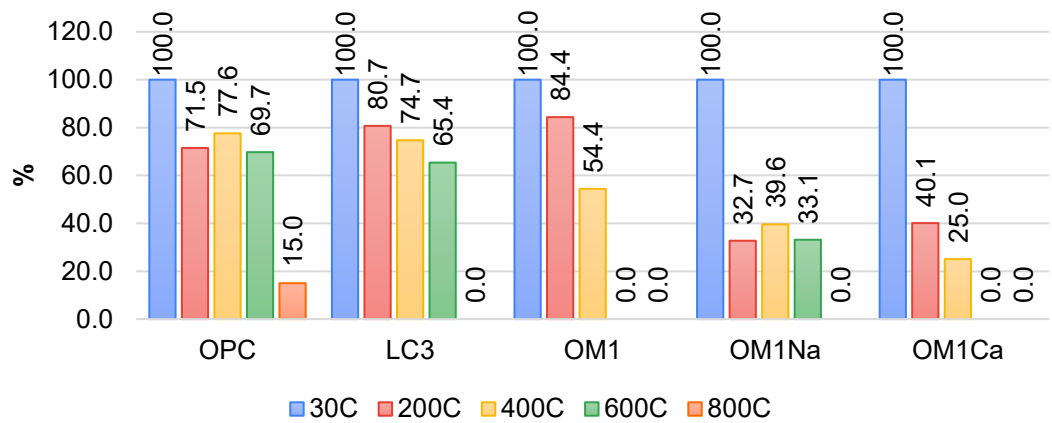


Figure 1: Residual compressive strength normalised to ambient temperature strength (%).

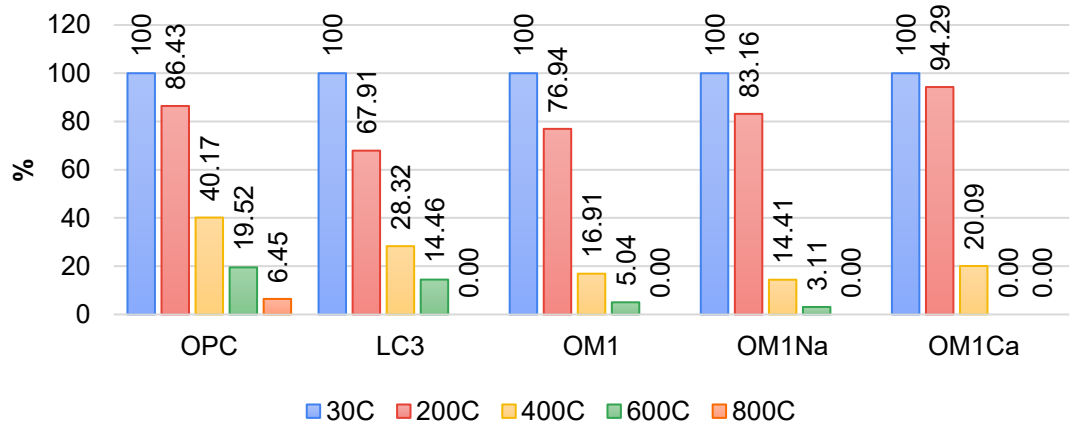


Figure 2: Residual flexural strength normalised to ambient temperature strength (%).

At 200°C, LC3 exceeds OPC due to katoite formation [2]; OM1 retains strength better because GGBFS forms thermally stable C-S-H. At 400°C, LC3 falls below OPC as C-(A)-S-H, katoite, and portlandite decompose; OM1 is worse, showing portlandite-driven microcracking. LC3/OM1 release heavy white smoke at 400–480°C from trapped steam. Above 600°C, OPC and LC3 persist while OM1 explosively spalls. Limestone decarbonation forms non-binding phases, destroying all LC3 binders; only OPC retains 15%. PCA Thermal Damage Index by unsupervised machine learning also shows internal damage outpaces visible surface deterioration. Flexural retention was consistently lower than compressive (at 400°C, LC3 retained 74.7% compressive but only 28.3% flexural), confirming compressive-only assessment overestimates residual capacity.

3.2 Spalling Behaviour

Table 1: Spalling observations at elevated temperatures.

Mix	400°C Cube	600°C Cube	600°C Prism	800°C
OPC	0/3	0/3	0/3	None
LC3	0/3	1/3	0/3	Thermal
OM1	0/3	3/3	0/3	
OM1Na	1/3	2/3	2/3	
OM1Ca	1/3	3/3	3/3	



Figure 3: Explosive spalling at 600°C.



Figure 4: Thermal spalling at 800°C.

Thus, OPC resisted spalling at all temperatures because its porous, permeable structure allowed gradual vapour escape. Only OM1Na/OM1Ca spalled at 400°C (30–35 min); at 600°C, all OM1 cubes spalled, but prisms survived. OM1Na showed 2 cubes and 2 prisms spalled; OM1Ca spalled completely. Alkali activation forms ultra-dense gels trapping vapour. Cubes spall more than prisms due to lower surface-area-to-volume. At 800°C, all LC3 collapsed from limestone decarbonation. This reveals a paradox: pore refinement boosting ambient strength becomes a severe fire liability [3].

4. Conclusions

Optimised LC3–GGBFS mortars improve ambient performance but not fire resistance. Further, poor performance is due to alkali activation, not GGBFS. Pore refinement boosting durability traps vapour, causing catastrophic spalling. Geometry critically influences performance: cubes spall earlier than prisms. Flexural retention is consistently lower than compressive; compressive-only assessment overestimates residual capacity. These optimised LC3 mortars are unsuitable for structural fire-safety applications without further modification.

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EVALUATION OF FIRE RESISTANCE OF OPTIMIZED LC3 MORTAR WITH ALKALI ACTIVATED SLAG

U. Thulajah^{1*}, B.M.P.M. Balasooriya¹, T.G.P.L. Weerasinghe¹
¹ Department of Civil Engineering, University of Moratuwa, Sri Lanka

Introduction

LC3 offers 50% clinker replacement with lower CO₂ emissions but suffers from poor fire resistance. Prior optimization produced OM1 (no alkali activation), OM1Na (Na₂SO₄ activation), and OM1Ca (Ca(OH)₂ activation). This study evaluates their fire resistance at 200–800°C.

Objectives

To assess the high-temperature fire resistance of GGBFS-blended LC3 mortars with and without alkali activation, by quantifying residual mechanical properties, thermal degradation mechanisms, and spalling vulnerability under controlled heating conditions.

Methodology

Five mortar mixes (OPC, LC3, OM1, OM1Na, OM1Ca) were cast as cubes and prisms at 1:2.75:0.6 binder:sand:water ratio. Specimens were cured 28 days, then heated at 5°C/min to 200, 400, 600, and 800°C with a 2-hour soak. Post-exposure assessments included residual compressive strength, flexural strength, mass loss, and spalling behavior.

Results

OM1 retained 84.4% compressive strength at 200°C, while OM1Na and OM1Ca retained only 32.7% and 40.1%. Alkali-activated mixes spalled explosively at 400°C; OPC never spalled. At 600°C, cubes exploded but prisms survived. Flexural retention was lower than compressive.

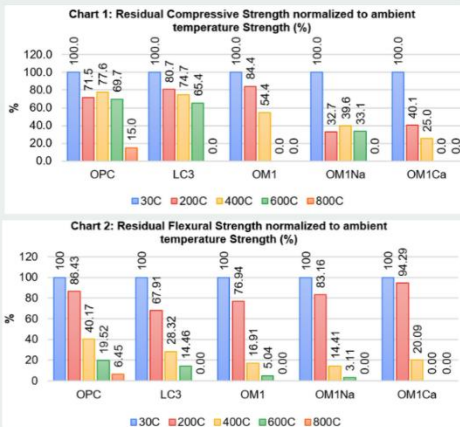


Table 1— Spalling Observations at Elevated Temperatures

Mix	400°C Cube	600°C Cube	600°C Prism	800°C
OPC	0/3	0/3	0/3	None
LC3	0/3	1/3	0/3	Thermal
OM1	0/3	3/3	0/3	Thermal
OM1Na	1/3	2/3	2/3	Thermal
OM1Ca	1/3	3/3	3/3	Thermal

Figure 1: Thermal spalling at 800°C



Figure 2: Explosive spalling at 600°C



Conclusion

Optimized LC3 mortars are unsuitable for structural fire-safety applications. Alkali activation causes explosive spalling, not GGBFS. Geometry critically influences survival: cubes spall earlier than prisms. Flexural retention is consistently lower than compressive, so compressive-only assessment overestimates residual capacity. Further modification is essential.

CORROSION PROTECTION PERFORMANCE OF ORGANIC INHIBITORS IN REPAIR MORTARS

Dhanushka Kobbekaduwa^{12*}, Ominda Nanayakkara², Janaka Perera¹

¹ Department of Civil Engineering, Sri Lanka Institute of Information Technology, Colombo

² Department of Civil Engineering, Xi'an Jiaotong-Liverpool University, Suzhou, China

**Corresponding author: dhanushka.k@slit.lk*

Abstract

Reinforcement corrosion is a major durability concern in reinforced concrete structures, contributing to cracking, deterioration, and loss of structural performance. Organic corrosion inhibitors incorporated into repair mortars provide a potentially simple and effective approach for mitigating reinforcement corrosion. This study investigated two inhibitors, an amino alcohol-based inhibitor and a sodium gluconate-based inhibitor, in four repair mortar systems: polymer-modified, conventional cementitious, fine-grained, and alkali-activated geopolymer mortars. The inhibitors were incorporated at dosages of 0.5%, 1%, and 2% by volume. Cylindrical mortar specimens containing embedded steel reinforcement were subjected to accelerated corrosion using an impressed current technique in chloride solution. Electrical resistance and time to crack initiation were used to evaluate corrosion protection. The inhibitors generally increased electrical resistance and significantly delayed corrosion-induced cracking compared with the corresponding control mortars. However, resistance did not increase proportionally with inhibitor dosage, indicating interaction between inhibitor concentration and mortar microstructure. Despite this variation, the considerable delay in crack initiation demonstrated the effectiveness of the protective adsorption layer formed on the reinforcement surface. The findings highlight the importance of inhibitor-mortar compatibility and dosage selection in developing durable repair systems for corrosion-damaged reinforced concrete structures.

Keywords: Reinforced concrete, Durability, Impressed current, Crack initiation, Chloride exposure

1. Introduction

Reinforcement corrosion is one of the primary causes of deterioration in reinforced concrete (RC) structures. Corrosion products generated around reinforcement induce expansive stresses, leading to cracking, delamination, and spalling of the cover and eventual deterioration of structural performance [1]. Organic corrosion inhibitors (OCIs) incorporated into cementitious materials provide a comparatively simple approach for corrosion protection. These compounds adsorb onto the reinforcement surface and form a protective layer that restricts electrochemical corrosion reactions [2].

The effectiveness of an OCI can depend considerably on the composition and microstructure of the surrounding repair material. Consequently, an inhibitor that performs effectively in one mortar system may not provide equivalent performance in another. This study therefore evaluates two admixed OCIs in four repair mortar systems under accelerated chloride-induced corrosion. The influence of inhibitor type and dosage on electrical resistance and corrosion-induced crack initiation was investigated to identify compatible OCI-mortar combinations for durable repair applications.

2. Experimental Programme

Four repair mortar systems were investigated: polymer-modified (P), conventional cementitious (C), fine-grained (F), and alkali-activated geopolymer (G) mortars. These four mortars have different compositions from each other. Two OCIs were considered: a commercially available amino alcohol-based inhibitor (AA) and a sodium gluconate-based inhibitor (SG). Each inhibitor was incorporated during mixing at dosages of 0.5%, 1%, and 2% by volume, together with control specimens containing no inhibitor.

Cylindrical specimens measuring 50 mm in diameter and 100 mm in height were prepared with a centrally embedded 10 mm diameter deformed steel bar. Accelerated corrosion was induced using an impressed current technique in which the embedded reinforcement acted as the anode and a stainless-steel plate acted as the cathode. Specimens were submerged in 3.5% NaCl solution and subjected to a constant current density of $200 \mu\text{A}/\text{cm}^2$ for 336 hours, corresponding to a theoretical steel mass loss of approximately 5%. Voltage measurements were converted to electrical resistance using Ohm's law, while the time to the first visible corrosion-induced crack was recorded. Three specimens were tested for each group, and average values were used for evaluation after a 28-day water-curing period. The experimental configuration for voltage measurement under constant current is shown in Figure 1.

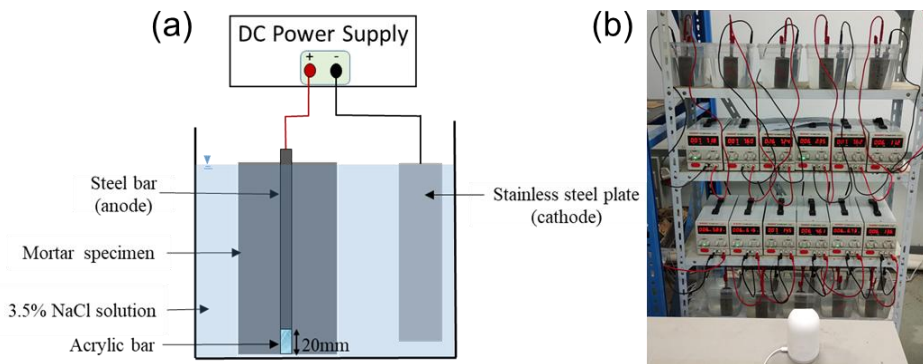


Figure 1: (a) Schematic view and (b) experimental setup of the impressed current measurements.

3. Results and Discussion

The incorporation of OCIs generally increased the electrical resistance of the repair mortars compared with their corresponding controls, indicating improved resistance to the ongoing corrosion process. However, the relationship between inhibitor dosage and electrical resistance was not linear. In several mortar systems, increasing inhibitor dosage reduced resistance. This behaviour was associated with inhibitor-induced changes in mortar microstructure, particularly increased void content at higher concentrations, which can facilitate chloride ingress and reduce matrix resistance.

Despite these variations in electrical resistance, both inhibitors substantially delayed corrosion-induced crack initiation, as shown in Figure 2. For the polymer-modified mortar, AA and SG increased cracking time by approximately 80% and 100%, respectively. More pronounced improvements were obtained in the other mortar systems. AA delayed cracking by approximately 400% in both the conventional cementitious and fine-grained mortars and by approximately 155% in the geopolymer mortar.

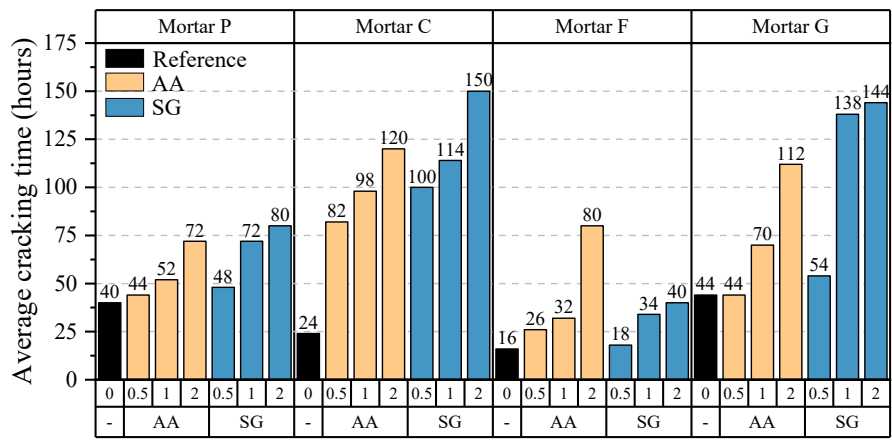


Figure 2: Cracking time of repair mortars with corrosion inhibitors.

The cracking-time results show that corrosion protection was not governed solely by the transport properties of the mortar matrix. Even where electrical resistance decreased at higher inhibitor dosages, crack initiation was considerably delayed. This indicates that the protective adsorption layer formed by the OCIs on the steel surface provided a dominant corrosion-inhibiting mechanism. The response nevertheless varied among mortar systems, confirming that inhibitor chemistry, dosage, and compatibility with the repair matrix should be considered together when selecting OCI-based repair systems.

Among the investigated systems, the conventional cementitious and fine-grained mortars exhibited particularly strong crack-delay responses with AA. The geopolymer mortar also showed a substantial improvement, while the polymer-modified mortar benefited from both inhibitor types. These observations demonstrate that OCI addition can enhance corrosion protection across chemically different repair matrices, although the optimum dosage cannot be selected from inhibitor concentration alone.

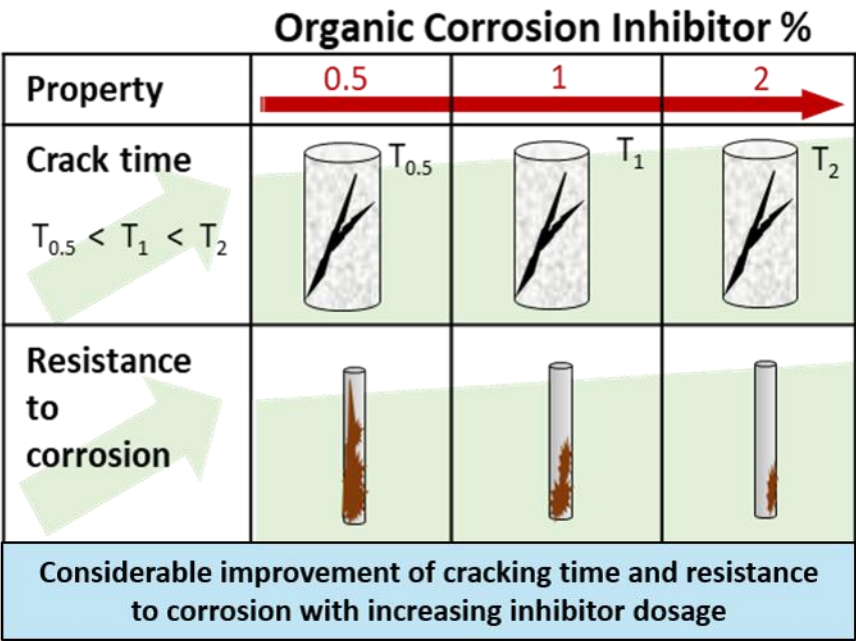
4. Conclusions

This study evaluated amino alcohol- and sodium gluconate-based OCIs in four repair mortar systems under accelerated chloride-induced corrosion. Both inhibitors generally improved corrosion resistance and significantly delayed corrosion-induced cracking. The magnitude of improvement depended on mortar type, inhibitor chemistry, and dosage, with the conventional cementitious and fine-grained mortars exhibiting particularly substantial crack delays with the amino alcohol-based inhibitor. Although higher inhibitor concentrations did not consistently increase electrical resistance, the significant extension of crack initiation time demonstrated the dominant protective effect of OCI adsorption on the reinforcement surface. Appropriate selection of compatible inhibitor-mortar systems can therefore contribute to more durable and sustainable repair strategies for corrosion-damaged RC structures.

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EVALUATING IRRIGATION WATER SUPPLY RELIABILITY UNDER VARIABLE RAINFALL: THE ROLE OF RESERVOIR REGULATION AND MANAGED DIVERSION IN THE NACHCHADUWA SUB-CATCHMENT, SRI LANKA

Tharuka Heshani^{1,2*}, Chamal Perera²

¹ Lanka Hydraulic Institute Ltd, Sri Lanka

² Department of Civil Engineering, University of Moratuwa, Sri Lanka

**Corresponding author: tharukapunchihewa@gmail.com*

Abstract

Irrigation water availability in Sri Lanka's dry zone is affected by seasonal and inter-annual rainfall variability, but reservoir storage and trans-basin diversions can buffer these fluctuations. This study evaluates the role of reservoir regulation and managed diversion in irrigation water reliability in the Nachchaduwa sub-catchment, Sri Lanka. A continuous semi-distributed HEC-HMS model was developed using historical rainfall, reservoir-level and diversion data to represent rainfall-runoff processes, storage and managed water transfers. The model reproduced reservoir-level dynamics with NSE values of 0.453 and 0.626 for calibration and validation, respectively, with RSR of 0.70 and 0.60 and PBIAS of 0.36% and 0.05%. Although calibration performance was limited for short-term variability, the low PBIAS indicated close agreement in overall water balance. Seven-day cumulative rainfall showed the strongest, but weak, association with diversion, indicating that diversion is also influenced by reservoir storage and operational decisions. Despite rainfall variability, irrigated area remained comparatively stable, highlighting the buffering role of reservoir regulation and managed diversion. The results demonstrate that irrigation reliability is governed by the interaction of local rainfall, external water transfers, reservoir storage and operational management.

Keywords: Climate change, Reservoir operation dynamics, Trans-basin water diversion, Hydro-climatic variability, Irrigation system resilience

1. Introduction

Rainfall in Sri Lanka's dry zone exhibits strong seasonal and inter-annual variability, creating uncertainty in irrigation water availability. Reservoir storage and trans-basin diversions can buffer this variability by regulating inflows and supporting water allocation according to demand [1]. The Nachchaduwa irrigation system is influenced by local runoff, reservoir storage and managed external diversion, making irrigation reliability dependent on both hydro-climatic conditions and water-management decisions. This study evaluates how rainfall variability, reservoir regulation and managed diversion interact to maintain irrigation water reliability in the Nachchaduwa sub-catchment.

2. Study Area and Methodology

The Nachchaduwa sub-catchment covers approximately 599 km² within the Malwathu Oya River Basin and forms part of the dry-zone irrigation system of Sri Lanka. The system receives water from both local catchment runoff and managed upstream diversion [2]. Daily rainfall data (1960–2014), reservoir water levels and diversion records were analysed to characterise hydro-climatic variability and system response. A continuous semi-distributed HEC-HMS model was developed to simulate rainfall-runoff processes, reservoir storage and managed water transfers, with 2010–2011 observations used for calibration and 2012–2013 for

validation. Model performance was assessed using NSE, RSR and PBIAS following Moriasi et al. [4]. Lagged and cumulative rainfall indices were also compared with diversion records to examine their association. In addition, community- and policy-level questionnaires were conducted to capture local experiences of irrigation water availability and stakeholder perspectives on water management.

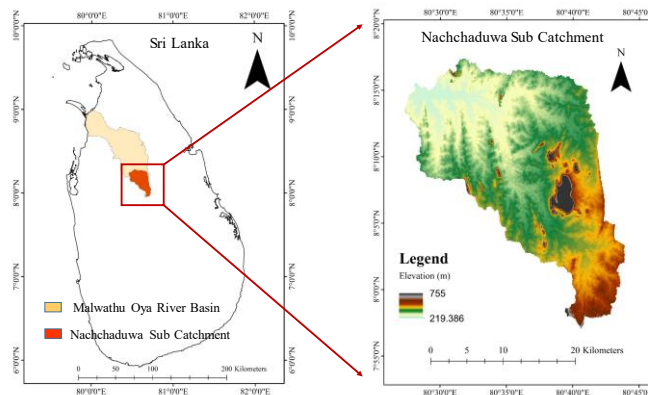


Figure 1: Study area.

3. Results and Discussion

The HEC-HMS model reproduced observed reservoir-level dynamics with NSE of 0.453 and 0.626 for calibration and validation, respectively; corresponding RSR values were 0.70 and 0.60, and PBIAS values were 0.36% and 0.05% [4]. While the calibration NSE indicates limited representation of short-term variability, the low PBIAS confirms close agreement in overall water balance. Seven-day cumulative rainfall showed the strongest association with diversion among the rainfall indices examined, although the relationship remained weak, indicating that diversion is additionally controlled by reservoir storage and operational decisions. Diversion capacity increased up to the 150–200 mm rainfall category before declining at >200 mm, suggesting non-linear operational or hydraulic controls. Despite substantial rainfall variability, irrigated area remained comparatively stable, indicating buffering through reservoir storage and managed diversion [1]. Community responses also indicated greater water-related conflicts during storage-limited periods. Overall, irrigation reliability is governed by the interaction of local rainfall, external water transfers, reservoir storage and seasonal operational demand.

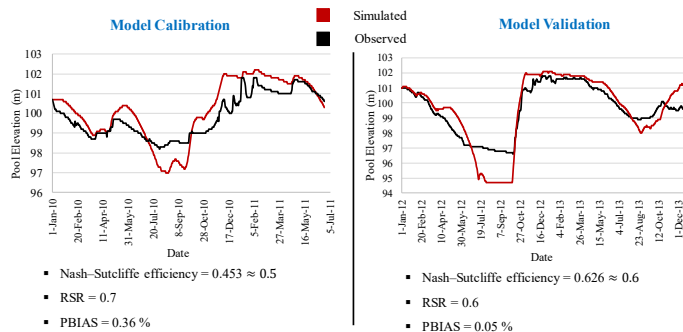


Figure 2: Rainfall–diversion relationship and reservoir response.

Table 1: Percentage occurrence according to rainfall bins.

Rainfall Bins (mm)	Occurrence %	Average Diversion Capacity (MCM)
0-20	63%	0.07
20-50	16%	0.11
50-100	13%	0.15
100-150	5%	0.16
150-200	2%	0.21
above 200	1%	0.13

4. Conclusions

The results demonstrate that irrigation water reliability in the Nachchaduwa sub-catchment is not governed by local rainfall variability alone. Instead, the system response reflects the combined effects of local rainfall, managed external inflows, reservoir storage and operational allocation. The HEC-HMS model reproduced the overall reservoir water balance with very low volume bias, although the calibration performance indicates limitations in representing short-term reservoir-level fluctuations. The weak rainfall–diversion association further indicates that managed diversion and reservoir operation play an important role in regulating water availability beyond the direct influence of local rainfall. The comparatively stable irrigated area under variable rainfall highlights the buffering function of reservoir regulation and managed water transfers. These findings emphasise the importance of incorporating both hydro-climatic variability and the reliability of externally supplied water when assessing irrigation water security in trans-basin irrigation systems.

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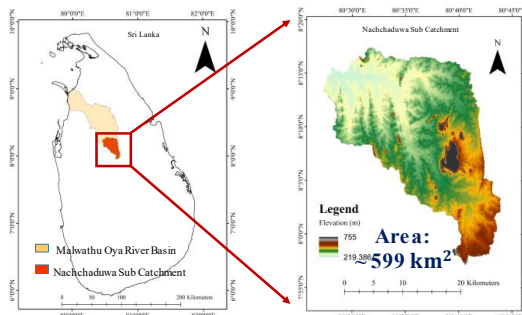
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Irrigation Water Supply Reliability Under Variable Rainfall; The Role of Reservoir Operations and Managed Diversion in Nachchaduwa Sub-catchment, Sri Lanka

Reservoir storage and managed diversion decouple irrigation water availability from short-term rainfall variability, sustaining stable irrigation even under climate variability.

1. Study Area



2. Methodology



Data: Daily Rainfall (1960-2014), Temperature, Reservoir Water Levels, Diversion Water Volumes



Hydrological Model: HEC-HMS, continuous, semi distributed model with reservoir & diversion



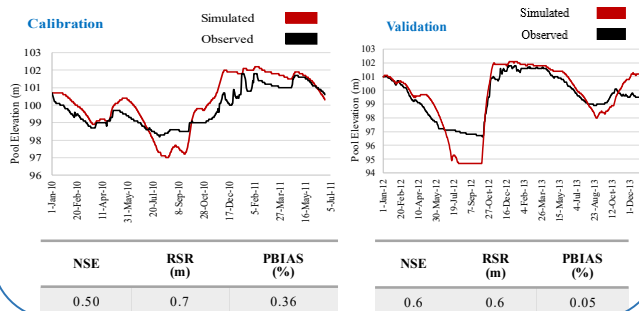
Rainfall-Diversion Analysis: Lagged cumulative rainfall indices vs diversion water volumes



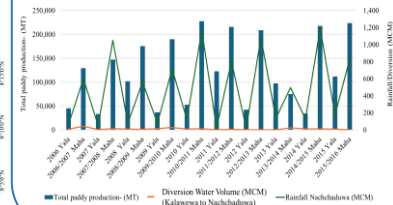
Policy Level & Community Survey: Questionnaire & interviews on water allocation & conflicts

3. Results

Model Performance

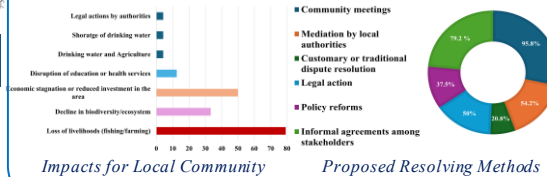


Rainfall-Diversion Relationship

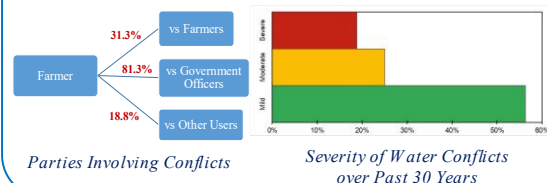


✓ Large inter annual rainfall variability but irrigated area remains relatively stable due to managed diversion

Policy Level Questionnaire Responses



Community Level Questionnaire Responses



4. Conclusion

- Reservoir regulation buffers rainfall variability and sustains irrigation water availability.
- Storage management and institutional-community coordination strengthen drought resilience.
- Adaptive management and inter-basin transfers enhance future water security under climate change.

DEVELOPMENT OF A WASTEWATER MANAGEMENT FRAMEWORK FOR ENVIRONMENTAL LABORATORIES IN SRI LANKA

D.G.M.A. Godagamapala^{1*}, S.M. Imbulana², J.M.A. Manatunge²

^{1,2} Department of Civil Engineering, University of Moratuwa, Moratuwa, Sri Lanka

**Corresponding author: manilkaashini00@gmail.com*

Abstract

Laboratories conducting environmental analyses generate highly toxic wastewater containing strong mineral acids, heavy metals, organic solvents, and residual analytical reagents. Yet, no specific national guidelines exist for managing and discharging it. This study assessed wastewater management practices at six major environmental laboratories in Sri Lanka through questionnaire surveys and site assessments, and conducted physicochemical and heavy-metal analyses of effluent from two representative sites. Survey results show that 66.7% of laboratories discharged wastewater without treatment, while 80% were unaware of applicable regulations. Laboratory analyses recorded $\text{pH} = 3.11 \pm 3.68$, low biodegradability ($\text{BOD/COD} < 0.3$), and heavy-metal concentrations exceeding Central Environmental Authority (CEA) Schedule I inland surface-water discharge standards, with maximum exceedances of 7 times for iron, 5 times for chromium, and 7 times for manganese. The chemical oxygen demand (COD) analysis was identified as the principal source of chromium contamination of laboratory wastewater. Based on the empirical findings of the study, a five-pillar and three-tier wastewater management framework was proposed, incorporating Green Analytical Chemistry, five-stream waste segregation, tiered on-site treatment, documentation of regulatory compliance, and institutional capacity building. The framework is scalable from small-scale academic laboratories to large government institutions and uses locally available materials and existing regulatory infrastructure, offering a practical pathway toward safer and more responsible laboratory wastewater management.

Keywords: Laboratory effluent management, Wastewater discharge standards, Heavy-metal contamination, Green analytical chemistry, Institutional capacity building

1. Introduction

Environmental analytical laboratories, including those operated by regulatory authorities, national research institutes, and university departments, form a network of facilities that generate wastewater as a direct by-product of routine analytical work. Unlike industrial effluent, laboratory wastewater is low in volume but high in toxicity, containing a highly variable mixture of strong acids, heavy-metal standards, and organic solvents that render conventional biological treatment largely ineffective. Within the context of Sri Lanka, the Central Environmental Authority (CEA) has established discharge standards under the National Environmental Act, yet their application to laboratory-scale effluent remains poorly enforced, and most facilities dispose of contaminated liquid waste directly into drains without pre-treatment due to limited awareness and the absence of laboratory-specific guidance. This study addresses this gap by developing a wastewater management framework for environmental laboratories in Sri Lanka, grounded in empirical data from a questionnaire survey of six laboratories and physicochemical analysis of wastewater from two selected institutions.

2. Materials and Methods

A mixed approach was adopted: 1) a questionnaire survey of six environmental laboratories was used to assess current segregation, treatment, monitoring, and regulatory-awareness practices; and 2) two representative case-study laboratories were selected for detailed wastewater characterisation and heavy-metal analysis of wastewater collected from the laboratories. The questionnaire was developed from the study objectives and relevant literature and was reviewed by the research supervisor for relevance and clarity before deployment.

3. Results and Discussion

Survey responses revealed critical deficiencies in laboratory wastewater management: 67% of laboratories discharged wastewater directly to sinks or sewers without treatment, 50% did not segregate waste streams, and 80% were unaware of applicable regulations. None of the laboratories adopted any standardised wastewater management practices. These findings directly informed the proposed framework: the lack of segregation supported the inclusion of source segregation, untreated discharge supported tiered on-site treatment, and limited regulatory awareness supported the regulatory compliance and documentation pillar.

Wastewater sampling confirmed these deficiencies empirically. In Case Study 1, the sample pH ranged from 0.83 to 1.15, far below the CEA permissible range of 6.0–8.5, with BOD/COD ratios of 0.0–0.27 confirming non-biodegradability. In Case Study 2, all ten sampling points were non-compliant with the CEA standard for pH (range: 2.02–5.10), and COD exceeded the limit of 250 mg/L at 60% of the points, indicating a maximum of 560 mg/L. Maximum concentrations of iron and manganese were nearly 7 times the respective CEA limits, whereas the same for chromium was nearly 5 times (Table 1). However, lead remained compliant throughout. Chromium contamination was traced primarily to dichromate-based COD determination (APHA 5220); substituting this with KMnO₄-based or micro-COD kits would eliminate the dominant chromium waste stream at minimal cost.

Table 1: Key wastewater quality parameters vs. CEA wastewater effluent discharge standards.

Parameter	CEA limit	Case Study 1	Case Study 2	Max. exceedance
pH	6.0–8.5	0.83–1.15	2.02–5.10	Non-compliant
COD (mg/L)	≤250	up to 280	156–560	2×
Fe (ppb)	≤3,000	–	438–22,001	7×
Cr (ppb)	≤500	–	98–2,478	5×
Mn (ppb)	≤1,000	–	56–7,101	7×

These findings highlight laboratory wastewater as a significant but consistently under-managed environmental hazard. BOD/COD ratios below 0.3 indicate poor biodegradability and limited suitability for biological treatment alone [5], while the absence of segregation and monitoring at most institutions suggests that the main barrier to effective wastewater management is institutional rather than technical.

4. Proposed Wastewater Management Framework

Based on the empirical findings and a review of key literature [2,4–6], a five-pillar, three-tier framework is proposed following a prevention-first hierarchy of eliminate, reduce, reuse, treat, and dispose (Figure 1).



Figure 1: Proposed five-pillar wastewater management framework.

Pillar 1 (Source Reduction) applies Green Analytical Chemistry (GAC), the application of green chemistry principles to analytical methods to reduce reagent use, waste, hazards, and energy consumption [2]. It includes microscale procedures and replacement of the dichromate COD method. Pillar 2 (Waste Segregation) uses a five-stream classification of strong acids, alkalis, heavy metals, biological waste, and general rinse water. Pillar 3 (On-site Treatment) specifies neutralisation, precipitation, and polishing, with autoclave sterilisation for biological waste. Pillar 4 (Regulatory Compliance) requires Scheduled Waste Management and Environmental Protection Licences with five-record documentation. Pillar 5 (Capacity Building) designates a Laboratory Waste Management Officer and a structured training programme. The framework scales across three tiers by daily effluent volume: Tier 1 for small academic laboratories (<10 L/day), Tier 2 for mid-scale government laboratories (10–100 L/day), and Tier 3 for large government institutions (>100 L/day), with progressively greater treatment, monitoring, and standard operating procedures (SOPs). This three-tier implementation structure is also summarised in the graphical abstract.

5. Conclusions

This study provides empirical evidence that environmental laboratory wastewater poses a significant and under-managed risk. Most surveyed laboratories discharged wastewater without monitoring or segregation, and effluent samples collected from laboratories substantially exceeded the national wastewater effluent discharge standards, with concentrations reaching beyond 7 times the permissible limits for some heavy metals. The findings revealed that biological treatment alone is insufficient, given the consistently low BOD/COD ratios observed, whereas physicochemical treatment would be scientifically appropriate. The standard COD analysis resulted in chromium contamination of wastewater, which can be addressed by shifting to low-cost alternative approaches. Although detailed characterisation was limited by instrumental availability, testing time, and restricted disclosure of some wastewater quantities and disposal practices, the combined survey and case-study evidence informed a five-pillar wastewater management framework that offers a practical, evidence-based, scalable pathway toward standards-compliant laboratory wastewater management.

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Development of wastewater management framework for environmental laboratories

THE PROBLEM

- Environmental laboratories generate low volume but high toxicity wastewater containing acids, alkalis, heavy metals, organic solvents, etc.
- Majority discharge untreated effluents to sinks or sewers.
- Lack of awareness, infrastructure and laboratory-specific guidelines.
- Risk to environment, public health and non-compliance with regulatory standards.



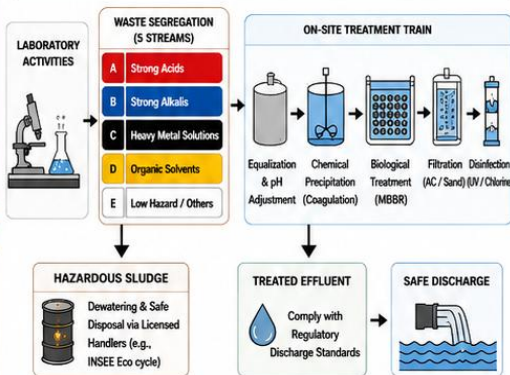
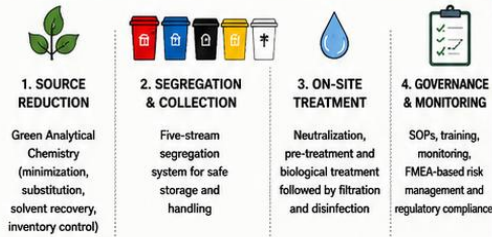
STUDY APPROACH



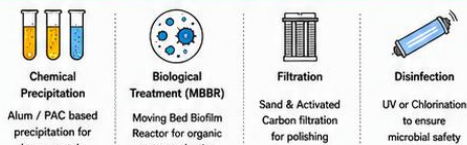
MAJOR CONTAMINANTS IDENTIFIED

- pH**: Extreme Acidity (pH < 2)
- COD**: High COD (Organic / Inorganic)
- Cr**: Chromium (Cr)
- Fe**: Iron (Fe)
- Mn**: Manganese (Mn)
- Other Metals & Chemicals**

PROPOSED WASTEWATER MANAGEMENT FRAMEWORK



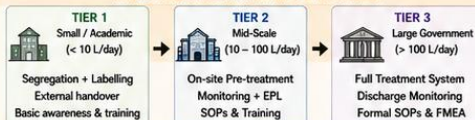
TREATMENT TECHNOLOGIES USED



PERFORMANCE GOALS

- | | | |
|---|---|---|
| <ul style="list-style-type: none"> ✓ pH: 6.0 – 8.5 ✓ COD: < 250 mg/L ✓ BOD: < 30 mg/L ✓ TSS: < 50 mg/L | <ul style="list-style-type: none"> ✓ Total Cr: < 0.5 mg/L ✓ Fe: < 3 mg/L ✓ Mn: < 1 mg/L ✓ Pb: < 0.05 mg/L | <p>→ Comply with Regulatory Discharge Standards</p> |
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THREE-TIER IMPLEMENTATION APPROACH



ENABLING ELEMENTS



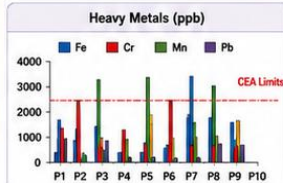
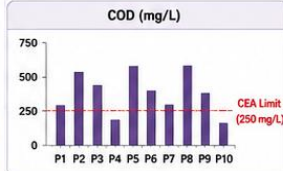
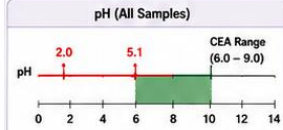
STAKEHOLDERS & IMPLEMENTERS



EXPECTED OUTCOMES

- Reduced environmental pollution
- Improved regulatory compliance
- Resource conservation & cost savings
- Safer laboratories and communities
- Contribution to sustainable laboratory practices

KEY RESULTS (CASE STUDIES)



KEY FINDINGS

- 66.7% discharge directly to sink/sewer without treatment
- 80% unaware of national wastewater regulations
- Extreme pH (2.0 – 5.1) in all samples (100% non-compliance)
- 60% samples exceed COD limit (250 mg/L); BOD/COD < 0.3 (non-biodegradable)
- High heavy metals: Fe (90%), Cr (70%), Mn (80%) exceed CEA limits

ENVIRONMENTAL & SOCIO-ECONOMIC BENEFITS

- Protection of water bodies and ecosystems
- Compliance with national regulations
- Cost savings through source reduction and resource recovery
- Improved laboratory safety and awareness
- Supports sustainable development goals

OPTIMISING BUILDING DESIGN FOR CINNAMON OIL REFINERY CENTRES: A STUDY OF AIR CIRCULATION AND OCCUPATIONAL SAFETY

Poornitha Hapuarachchi^{1*}, Praween Madusanka¹, Avishka Siriwardana¹, V.L.E. Kalanika¹

¹ Department of Civil Engineering, Faculty of Engineering, University of Sri Jayewardenepura, Sri Lanka

**Corresponding author: chulabaya7@gmail.com*

Abstract

Cinnamon oil refinery centres in Sri Lanka are commonly operated in naturally ventilated, semi-enclosed buildings where boilers, steam distillation units and cinnamon leaf storage can create localised heat accumulation and weak airflow regions. This study optimised the building design of such refinery centres by evaluating existing layout conditions, measured thermal and airflow data and computational fluid dynamics (CFD)-based design alternatives. Twelve refinery centres were initially observed and one representative refinery at Berathuduwa, Galle was selected for detailed investigation. Field data were used to prepare and validate an ANSYS Fluent model. The validated model was then applied to compare design variants including storage arrangement, boiler relocation, inlet opening, outlet opening, inlet-outlet combination, monitor roof, roof rise and optimised layouts. Results showed that one-sided ventilation improvements were not sufficient. The best performance was obtained by combining a clear inlet to outlet airflow corridor, non-obstructive storage placement, side-based boiler location and supportive roof volume. The study proposes practical guidelines for improving natural ventilation, reducing worker-zone thermal exposure and supporting occupational safety in small- and medium-scale cinnamon oil refinery centres.

Keywords: Computational fluid dynamics (CFD) simulation, Natural ventilation, Thermal comfort, Occupational safety

1. Introduction

Cinnamon oil refining is an important rural agro-industrial activity in Sri Lanka, especially in areas where cinnamon leaves are processed by steam distillation. The process depends on boilers, furnaces and distillation units, which release heat to the surrounding indoor space. Many traditional refinery buildings were constructed without detailed engineering consideration of airflow direction, opening arrangement, storage location or worker thermal safety. Consequently, heat may accumulate near the processing area and reduce thermal comfort for workers who remain close to the boiler zone during production.

The research problem is therefore not limited to the presence of heat sources. It is also connected with the spatial relationship between the inlet side, outlet side, boiler zone, chimney path, worker area and cinnamon leaf storage. If these elements are arranged poorly, fresh air may enter the building but fail to pass through the occupied zone and remove heat effectively. The purpose of this study was to assess this problem using field measurements and CFD analysis and to convert the findings into practical design guidance.

The aim of the research was to optimise the building design of cinnamon oil refinery centres by developing and validating design guidelines that improve air circulation and enhance occupational health safety. The objectives were to study existing layouts and natural ventilation strategies, identify airflow and heat accumulation challenges related to worker exposure, and simulate alternative building designs using CFD to develop improved design recommendations.

2. Literature Review

Industrial ventilation literature identifies airflow distribution as a key engineering control for reducing indoor heat and hazardous exposure in production spaces [1], [2]. In hot industrial environments, thermal comfort and worker safety are affected by air temperature, air velocity, heat source intensity and obstruction of ventilation paths. CFD is widely used in building and industrial ventilation studies because it can predict temperature fields, velocity distribution, stagnant zones and hot air plume movement before construction or modification [2], [3].

The Sri Lankan cinnamon industry is economically important, but published engineering studies on the indoor environment of cinnamon oil refineries are limited [4]. Previous studies on industrial buildings, biomass-related exposure and indoor air quality provide useful background, but they do not directly solve the layout-specific ventilation problem of small cinnamon refinery centres. This research addresses that gap by applying a validated CFD approach to a real refinery building and by translating the results into building layout guidelines.

3. Methodology

The methodology was developed to cover the three research objectives from field observation to design guideline development. First, preliminary visits were carried out at twelve cinnamon oil refinery centres in the Galle District. These visits were used to understand common building layouts, boiler locations, cinnamon leaf storage practices, opening configurations and worker operating zones. Informal discussions with owners and workers helped identify practical issues such as thermal discomfort near the processing area.

Based on the preliminary survey, one representative refinery centre at Berathuduwa, Galle was selected for detailed investigation. The existing building condition was documented through site observations, layout measurements and photographs. Environmental data were collected during the cinnamon oil production process because the indoor thermal condition changes when the boilers and distillation units are operating. Boiler temperature, steam distillation unit temperature, inlet air velocity and outlet air velocity were measured and processed to obtain representative boundary conditions.

A three-dimensional model of the existing refinery building was prepared using the observed layout, roof form, openings, boiler positions, distillation units, tanks, storage areas and worker zones. The internal air domain was then simulated in ANSYS Fluent. The boiler area was treated as the dominant heat source, while the measured inlet velocity and thermal data were used to represent site operating conditions. The main CFD outputs were plan-view temperature contours, velocity contours and vertical cross-section temperature contours at 0.5 m, 1.5 m and 2.5 m from the boiler. The 2.5 m section was used as the worker-zone assessment section.

The existing CFD model was validated using measured temperature values at six worker-zone points and measured outlet air velocity. The validation showed percentage errors below 10% for temperature, with an RMSE of approximately 3.396 °C and an outlet velocity error of approximately 7.11%. After validation, the same modelling approach was used to compare the existing layout, existing layout with storage, boiler middle case, inlet open, outlet open, inlet and outlet open, monitor roof, roof rise and optimised building layouts.

4. Results and Discussion

Field measurements confirmed that the boiler zone was the primary thermal source in the refinery building. The measured average boiler temperature was approximately 82.8 °C, while the steam distillation unit also acted as a secondary heat-releasing surface with an average temperature of about 44.58 °C. The average inlet air velocity was approximately 2.12 m s⁻¹,

but the measured outlet air velocity was much lower, about 0.225 m s^{-1} . This difference indicated that fresh air could enter the building, but the removal of heated air was weak.

Table 1: Summary of CFD design variant findings.

Design variant	Main observation	Performance
Storage	Airflow obstruction and localised heat zone.	Low
Boiler middle	Central heat concentration in occupied space.	Low
Inlet open	Fresh air entry improved but heat removal incomplete.	Moderate
Outlet open	Discharge improved but near source heat remained.	Moderate
Inlet + Outlet open	Cross ventilation improved and stagnation reduced.	High
Roof rise/Monitor roof	Upward heat movement improved but not sufficient alone.	Moderate

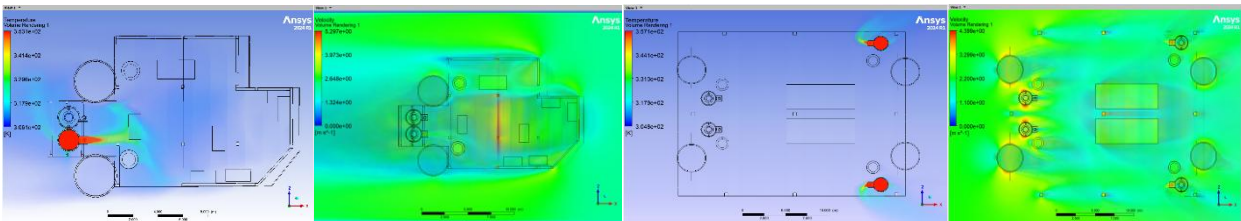


Figure 1: Plan view temperature and velocity contours used to compare ventilation behaviour. (Actual site condition).

Figure 2: Plan view temperature and velocity contours used to compare ventilation behaviour. (Optimised layout).

The existing CFD results supported the field observations. The temperature contour showed that heat generated near the boiler spread toward the interior and influenced the occupied zone. The velocity contour showed non-uniform airflow, with low-velocity regions in central and inner spaces (Figure 1).

The plan-view temperature contour shows that higher temperatures remain concentrated close to the boiler zones, while the rest of the interior stays within cooler bands. This means that the proposed arrangement reduces the spread of heat into the wider worker area and helps limit thermal discomfort in the occupied zone (Figure 2).

The velocity contour indicates a more continuous and better distributed airflow field across the refinery. Because the central zone is not blocked by major heat sources and the storage arrangement is more controlled, air can pass through the building with less stagnation. This supports better natural ventilation and more effective heat removal.

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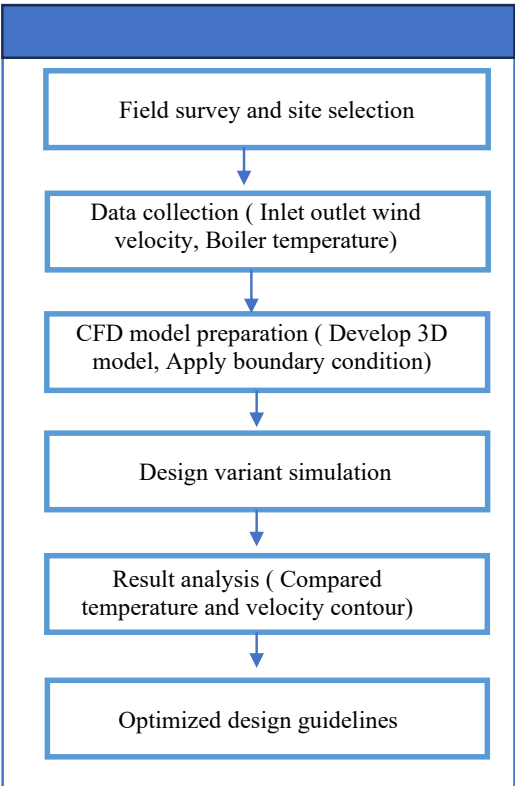
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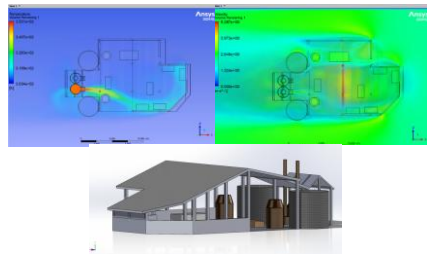
Graphical Abstract

Cinnamon oil refinery centers generate considerable heat during the oil extraction process, especially around boilers, furnaces and distillation units. In many existing refinery buildings, poor air circulation, unsuitable equipment arrangement and obstructed ventilation paths can cause heat accumulation within worker occupied areas. This can reduce thermal comfort and increase occupational safety concerns for workers who remain close to the processing zone for long periods. Therefore, this research focuses on optimizing the building design of cinnamon oil refinery centers by studying airflow behavior, temperature distribution and worker zone thermal conditions using CFD analysis.



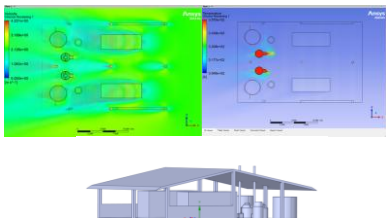
Result and Analysis

Existing refinery building



The figures show the existing refinery center configuration using the 3D building model together with plan view temperature , wind velocity contours. The existing refinery layout demonstrates poor airflow continuity and localized heat accumulation, indicating inadequate natural ventilation and the need for layout optimization.

Optimized layout



The figures show the optimized refinery center configuration using the 3D building model together with plan view temperature , wind velocity contours. The optimized layout was proposed based on the design variant comparison and showed improved airflow continuity, lower heat concentration, reduced stagnant zones, and better thermal conditions for workers.

INDOOR AIR QUALITY ASSESSMENT IN CINNAMON OIL REFINERY CENTRES IN SRI LANKA USING PTM 600: IDENTIFYING VENTILATION-RELATED HEALTH RISKS

Kavindu Lakshitha^{1*}, Praween Madusanka¹, Avishka Siriwardana¹, Erandi Kalanika¹

¹ University of Sri Jayewardenepura, Sri Lanka

*Corresponding author: kuglakshitha@gmail.com

Abstract

This field-based case study assessed indoor air quality and ventilation-related occupational exposure conditions in a selected cinnamon oil refinery centre in Beruthuduwa, Galle, Sri Lanka. A preliminary questionnaire survey was conducted among 48 respondents from 12 refinery environments (24 workers, 12 owners and 12 community members), including questions on symptoms experienced during refinery operation. Detailed monitoring was then carried out at one selected refinery during one complete, approximately seven-hour cinnamon oil distillation cycle. A PTM 600 portable monitor was used at five repeated operational points and one supplementary elevated leaf loading point to measure CO₂, CO, SO₂, NO₂, O₃, VOC, PM_{2.5}, PM₁₀, temperature and relative humidity; inlet and outlet air velocities were also measured. The highest CO process cycle mean occurred at the boiler zone (P2: 29.81 ppm), while the strongest particle levels occurred at the boiler and oil separator zones (PM_{2.5}: 415 and 404 µg/m³ at P2 and P3; PM₁₀: 433 and 435 µg/m³ at P2 and P3). The supplementary leaf loading point identified a short-duration, task-based pathway for hot humid vapour and particles. Measured mean air velocity was approximately 2.20 m/s at the inlet and 0.23 m/s at the monitored outlet; these point measurements indicate a large local airflow difference but do not by themselves quantify overall ventilation effectiveness. Among workers, headache, eye irritation and cough were reported by 100%, nasal symptoms by 95.8%, and dry/sore throat by 62.5%. These self-reported symptoms were used as supporting evidence and do not establish pollutant-specific causality. The findings support source control at the boiler and vessel opening, improved exhaust pathways, safer leaf loading practices, personal protective equipment, worker rotation and follow-up monitoring.

Keywords: Occupational exposure, Biomass combustion, Particulate matter, Industrial hygiene

1. Introduction

Indoor air quality is an important occupational health concern in small-scale industrial settings where combustion, heat generation, material handling, process vapours and limited engineered ventilation can produce changing exposure conditions. Cinnamon oil refineries use biomass combustion and steam distillation; the boiler, distillation vessel, oil separator and leaf handling areas can therefore generate smoke, gases, particles, heat and moisture. Limited scientific attention has been given to indoor air quality in traditional cinnamon oil refineries in Sri Lanka. This study combined questionnaire screening with zone-wise field measurements to characterise the refinery environment and develop practical control recommendations [1-3].

2. Literature Review

Industrial pollutant concentrations can vary substantially with task, source location and worker position [2]. Biomass combustion can release CO, CO₂, smoke and particulate matter, while handling activities can increase airborne particles [3]. Ventilation influences dilution and removal, but point air velocity measurements do not directly provide air change rate or whole-building ventilation effectiveness. CO₂ may provide contextual information on dilution, although in combustion-based workplaces it is not purely an occupancy marker [4]. The Sri Lankan Indoor Air Quality Guidelines provide interim screening values for common indoor

contaminants, including CO, PM_{2.5}, PM₁₀, NO₂ and TVOC with pollutant-specific averaging periods [6].

3. Methodology

The study used a two-stage design. First, 12 refinery centres were visited and a questionnaire was completed by 48 respondents (24 workers, 12 owners and 12 community members). The questionnaire recorded work/activity context and the frequency of symptoms experienced during refinery operation, including cough, breathing difficulty, eye irritation, headache, dizziness, throat discomfort and heat-related discomfort. Worker-only symptom percentages were used for occupational interpretation.

One refinery in Beruthuduwa, Galle was then selected for detailed monitoring. P1 was between the distillation vessels, P2 between the boilers, P3 in the oil separator room, P4 in the leaf storage area and P5 at the outdoor reference location. P6 was a supplementary point approximately 3 m above floor level near the leaf loading pathway. At the main points, the sampling inlet was approximately 1.2 m above the floor. Seven monitoring rounds were conducted over one approximately seven-hour distillation cycle. Each main point was monitored for 10 min per round; the first 2 min were excluded for stabilisation and the remaining 8 min were analysed. Data were logged every 10 s. Because the points were monitored sequentially rather than simultaneously, differences between points may reflect both spatial variation and temporal changes in process conditions; these effects cannot be completely separated.

Minimum and maximum values, process cycle mean concentrations and indoor/outdoor ratios were calculated from valid readings. Reference-value comparisons were treated as screening comparisons only because the intermittent point measurements did not match all prescribed guideline averaging periods. The 2022 Sri Lankan IAQ guideline for office/public places specifies, for example, CO 9 ppm (8 h), PM_{2.5} 50 µg/m³ (24 h), PM₁₀ 200 µg/m³ (24 h), NO₂ 0.080 ppm (8 h) and VOC 0.24 ppm [6].

4. Results and Discussion

The questionnaire showed a strong irritation-related symptom pattern among workers. Headache, burning/itchy eyes and cough were reported by all 24 workers at least sometimes; nasal symptoms were reported by 95.8% and dry/sore throat by 62.5% (Figure 1). These observations are consistent with a mixed irritant environment, but the self-reported cross-sectional questionnaire cannot attribute any symptom to a specific measured pollutant [5].

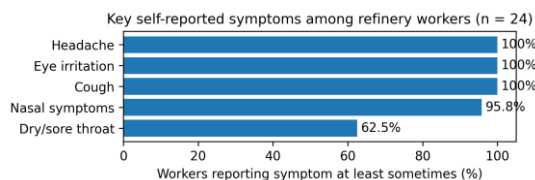


Figure 1: Key self-reported symptoms among refinery workers (n = 24).

CO₂ increased during later monitoring rounds at several points; however, because biomass combustion also contributes CO₂, it was interpreted only as a contextual dilution indicator rather than as a direct ventilation metric. VOC sensor responses were high across the site, including at the outdoor reference point. Consequently, the measurements demonstrate a widespread VOC signal but do not allow the refinery contribution or compound-specific source to be quantified confidently. P6 was monitored once during the elevated leaf loading task and showed short-duration increases in particles, SO₂ channel response and humidity; it is therefore interpreted as a task event measurement rather than a repeated process cycle average.

Table 1: Selected quantitative findings and reference-value context.

Indicator	Measured result	Interpretation
Air velocity	Inlet 2.20 m/s, monitored outlet 0.23 m/s	Large local velocity contrast; not a direct ventilation rate measurement.
CO	Highest process cycle mean: P2 = 29.81 ppm; P3 = 26.05 ppm	Boiler zone showed the strongest CO signal. Sri Lankan IAQ CO guideline is 9 ppm over 8 h [6].
PM _{2.5}	P2 = 415 µg/m ³ ; P3 = 404 µg/m ³	Strongest fine particle levels at boiler/oil separator zones. Sri Lankan IAQ guideline: 50 µg/m ³ over 24 h [6].
PM ₁₀	P3 = 435 µg/m ³ ; P2 = 433 µg/m ³	Strong coarse particle signal. Sri Lankan IAQ guideline: 200 µg/m ³ over 8 h [6].

The measured inlet/outlet velocity contrast was used only as contextual airflow evidence. Because velocity was measured at selected points rather than as a complete flow balance, it does not establish whole refinery ventilation ineffectiveness. Likewise, because monitoring locations were sequential, the observed point differences may include both spatial and temporal process variation.

5. Conclusions

This case study identified the strongest measured CO signal at the boiler zone and the strongest fine/coarse particle levels around the boiler and oil separator zones. The elevated P6 measurement also identified a short-duration, task-based exposure pathway during manual leaf loading. Worker-reported irritation symptoms were frequent and were compatible with the mixed exposure environment, but the study design does not establish pollutant-specific causality. High VOC responses at the outdoor point prevent confident attribution of VOCs primarily to the refinery, and the inlet/outlet point velocity measurements should not be interpreted as a quantitative ventilation rate assessment. The findings are limited to one refinery and one distillation cycle and are not representative of all cinnamon oil refineries in Sri Lanka. Based directly on the observed source and task patterns, priority controls are improved boiler smoke management, local extraction near the vessel opening, improved exhaust/cross-flow pathways, safer leaf loading practices, suitable personal protective equipment, worker rotation, training and follow-up monitoring.

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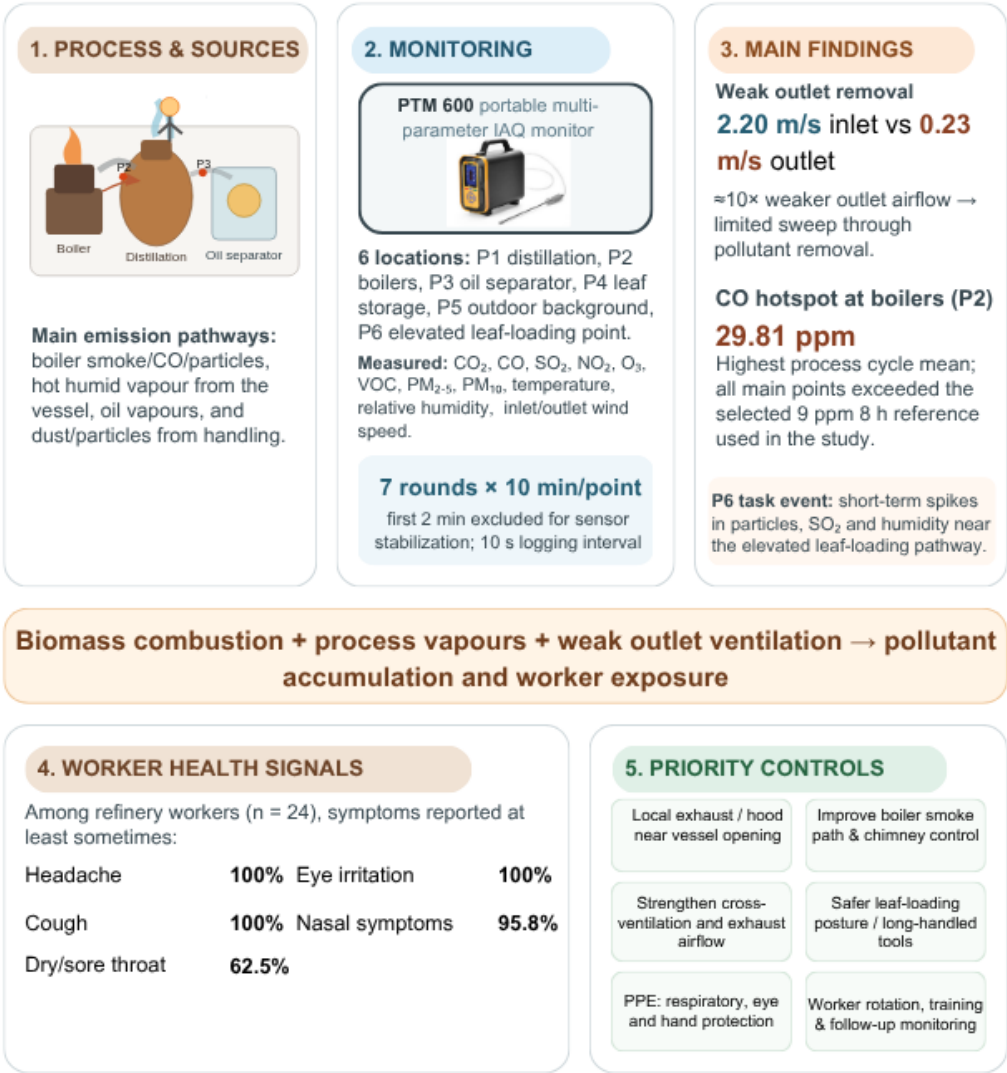
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Indoor Air Quality in a Cinnamon Oil Refinery

PTM 600 field assessment of ventilation related occupational exposure during a complete 7 h distillation cycle



INTEGRATION OF CLIMATE-INFORMED FLOOD HAZARD MODELLING AND COMMUNITY PERCEPTIONS FOR ADAPTIVE FLOOD RISK MANAGEMENT IN THE MAHA OYA RIVER BASIN, SRI LANKA

J. Vithurshika^{1,2*}, G.M.C.A. Perera^{1,3}

¹ UNESCO Madanjeet Singh Centre for South Asia Water Management, University of Moratuwa, Moratuwa 10400, Sri Lanka

² Department of Civil Engineering, University of Jaffna, Kilinochchi 42400, Sri Lanka

³ Department of Civil Engineering, University of Moratuwa, Moratuwa 10400, Sri Lanka

**Corresponding author: vithurshijeya96@gmail.com*

Abstract

The Maha Oya River Basin (MORB) in Sri Lanka experiences recurring floods threatening more than one million residents. However, flood management has traditionally emphasised physical hazard assessment, with limited integration of climate projections and community risk perceptions. This study develops a climate-informed flood hazard modelling framework and examines how exposure to hazard maps influences community risk perception, trust, and adaptive intent. Historical rainfall observations from four stations were quality-controlled, and bias-corrected CNRM-CM6-1-HR projections under SSP1-2.6 and SSP5-8.5 characterised future extreme rainfall. Gumbel frequency analysis and intensity-duration-frequency relationships generated 50-year design storms for historical and near-, mid-, and far-future periods, with the mid-future period selected as the critical period for both SSP1-2.6 and SSP5-8.5. HEC-HMS 4.13 and 2D HEC-RAS 6.6 generated flood hazard maps, achieving an accuracy of 0.92 and bias score of 0.99 during calibration against the May 2016 flood, and 0.83 and 1.42 during validation against the November 2025 flood. Simulated inundated area was 41.72 km² historically, rising to 51.26 km² (+22.86%) under SSP1-2.6 and 46.00 km² (+10.25%) under SSP5-8.5. Six flood-prone GN divisions in Pannala and Divulapitiya were identified, and 40 households within mapped inundation zones were purposively surveyed, giving a 97.6% response rate. Following exposure to the hazard maps, 87.5% of respondents reported improved understanding of flood risk, 85% reported increased concern about future flooding, and 97.5% expressed willingness to adopt adaptation measures. These findings highlight the potential value of integrating climate-informed hydrological and hydrodynamic modelling with participatory risk communication to improve risk awareness and support adaptive flood-risk management in the MORB.

Keywords: Climate change adaptation, CMIP6 projection, Hydrodynamic modelling, Risk perception, Participatory assessment

1. Introduction

Floods are among the most frequent and destructive natural hazards worldwide, and climate change may alter extreme precipitation and associated flood risks in coming decades [1]. In Sri Lanka, flood studies have generally focused on physical and topographic drivers of flooding, while comparatively less attention has been given to integrating future climate projections with community perspectives and risk perception. This creates a need for approaches that connect quantitatively modelled future flood hazards with the perceptions and adaptive intentions of affected communities.

The MORB supports more than one million residents and supplies water to fourteen water supply schemes. It has been classified as a high-stress basin because of its critical role in water supply and its vulnerability to climate change [2]. Areas such as Giriulla and Pannala regularly experience overbank flooding, while the November 2025 Ditwah flood event remains

prominent in the recent experience of affected communities. Prior MORB studies have focused primarily on low-flow conditions and domestic water security under climate change [3], whereas future flood hazards and their relationships with community risk perception remain comparatively underexplored.

Communities in hazard-prone areas often rely on past experience and local knowledge when preparing for floods; however, historical patterns may no longer adequately represent future risks under a changing climate. Hydrological and hydrodynamic models incorporating climate projections provide a scientific basis for assessing future flood scenarios, yet a persistent gap remains between technically derived hazard information and the perceptions, priorities, and adaptive capacities of affected communities. This study addresses that gap by developing climate-informed flood hazard maps for the MORB and evaluating how exposure to these maps influences community risk awareness, trust in scientific information, and willingness to adopt adaptive measures. The objectives of this study were to: (i) develop and validate a hydrological model for the MORB; (ii) simulate historical and selected future flood inundation under SSP1-2.6 and SSP5-8.5; and (iii) assess household flood experience, risk perception, understanding of model-derived flood-hazard information, and willingness to adopt adaptation measures.

2. Methodology

This study develops an integrated hydrological–hydrodynamic and community risk-perception framework for the MORB, which has a catchment area of 1,168 km², to link climate-informed flood hazard projections with community-level risk perceptions. Observed daily rainfall from four gauging stations (Ambepussa, Andigama, Aranayaka, and Eraminigolla; obtained from the Department of Irrigation) was subjected to missing-data analysis and consistency checks. The station rainfall data were subsequently converted to basin average rainfall using the Thiessen polygon method. Future precipitation was obtained from the CNRM-CM6-1-HR CMIP6 model (Copernicus Climate Data Store) for the historical period (2005–2014) and under SSP1-2.6 and SSP5-8.5 scenarios (2030–2100). The model precipitation was bias-corrected using quantile mapping. CNRM-CM6-1-HR was selected due to its high-resolution configuration and reported suitability for representing monsoon variability over Sri Lanka [4]. A single global climate model (GCM) was used to avoid potential smoothing of flood-peak magnitude and timing associated with ensemble averaging [5]. Extreme rainfall was characterised using Gumbel distribution fitting and intensity–duration–frequency (IDF) relationships to generate 50-year design storms for historical and near-, mid-, and far-future periods. The 50-year rainfall intensity was compared across these periods under both scenarios, and the mid-future period was selected as the critical period for subsequent HEC-HMS and HEC-RAS simulations.

HEC-HMS 4.13 was used to simulate rainfall-runoff processes. The model was calibrated against the December 2012 flood event and validated against the May 2016 event using streamflow records from the Giriulla gauging station. Simulated discharge hydrographs were subsequently used as inflow to a 2D HEC-RAS 6.6 model built on a 2 m resolution digital elevation model (DEM) with a 30 m × 30 m computational grid. The hydraulic model was calibrated against the observed inundation extent of the May 2016 flood and independently validated using the November 2025 flood event. Spatial model performance was evaluated using hits, misses, false alarms, correct negatives, accuracy, and bias score. Based on the flood-depth maps, six flood-prone GN divisions in Pannala and Divulapitiya DS Divisions were selected. A structured questionnaire survey was conducted among 40 households. The survey assessed demographic characteristics, past flood experience, trust in government agencies and scientific information, and flood risk perception before and after respondents were exposed to the model-derived flood hazard maps.

3. Results and Discussion

The quantile-mapping procedure substantially reduced the systematic bias in CMIP6 precipitation data. The resulting PBIAS values ranged from -0.327% to -0.328% across all four stations, indicating close agreement between bias-corrected model precipitation and observations. The hydrological model achieved a Nash–Sutcliffe efficiency (NSE) of 0.913 and a percent bias (PBIAS) of 8.67% during calibration, and an NSE of 0.866 and a PBIAS of 18.78% during validation, indicating good model performance. The coupled hydraulic model calibration produced close spatial agreement with the observed May 2016 inundation, yielding an overall accuracy of 0.92 and a bias score of 0.99, and, for the validation event (November 2025 flood), an accuracy of 0.83 and a bias score of 1.42. The historical scenario produced an inundated area of 41.72 km², increasing to 51.26 km² (+22.86%) under SSP1-2.6 and 46.00 km² (+10.25%) under SSP5-8.5 for the selected mid-future condition.

The household survey ($n = 40$) found that 75% of respondents had personally experienced flooding, most intensely recalling the 2025 event, and that 73% received no warning before past floods. Baseline trust in government agencies was very low for 85% of respondents, and expert-generated flood maps were viewed with suspicion before exposure. However, after viewing the hazard maps, 85% reported increased concern about future flooding, 87.5% indicated an improved understanding of local flood risk, and 97.5% felt authorities should take more action. In addition, 97.5% expressed willingness to adopt adaptation measures. Among respondents who selected specific adaptation options, 92.3% preferred flood insurance, 76.9% selected early warning systems, and 51.3% selected flood-protection structures. These results indicate that, despite low institutional trust, visual exposure to climate-informed hazard information can meaningfully shift risk perception and adaptive intent, supporting the case for coupling technical model development with participatory hazard communication.

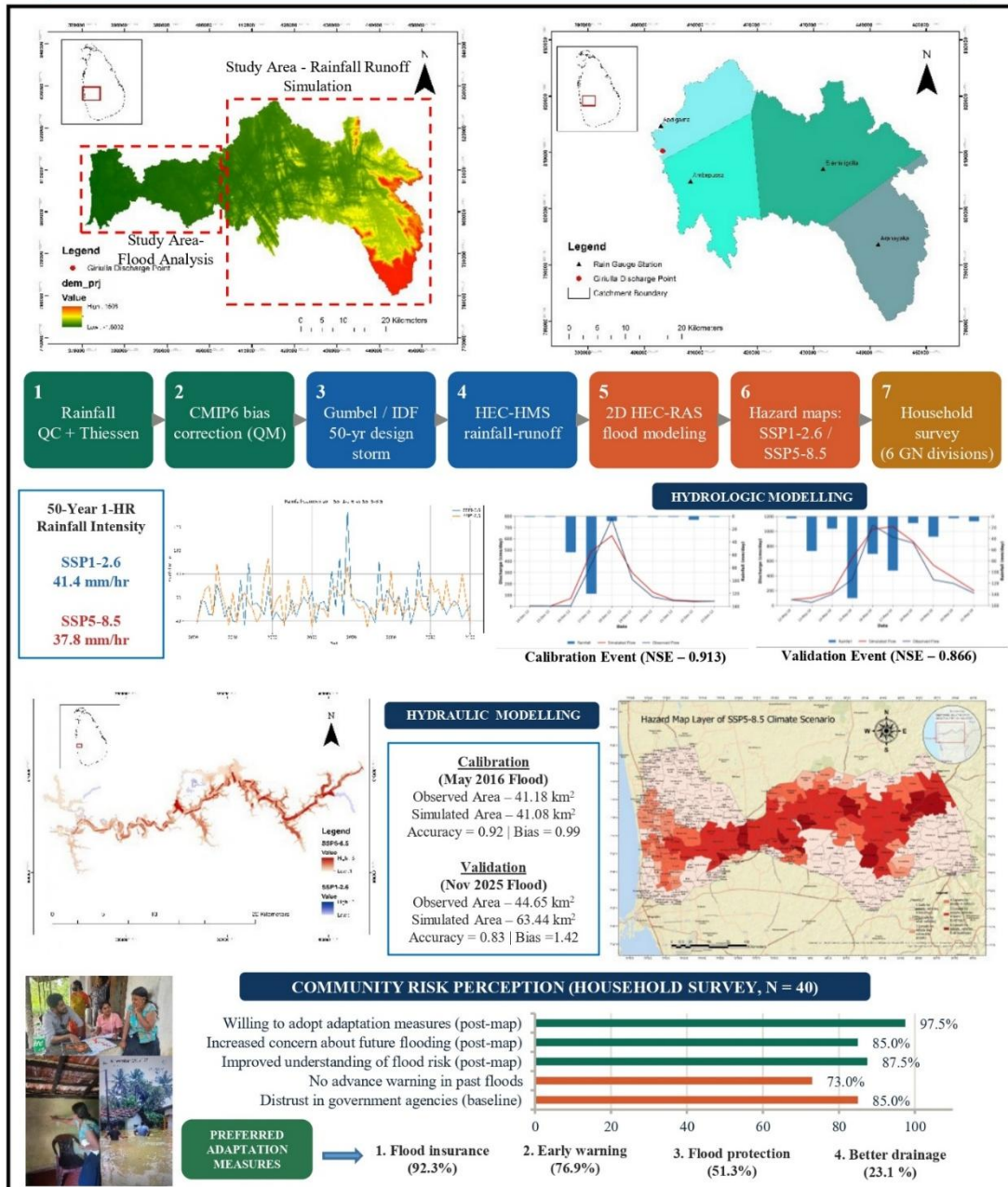
4. Conclusions

This study found that the simulated future flood extent in the MORB increased under both climate scenarios for the selected mid-future condition, with the larger increase occurring under SSP1-2.6. The surveyed communities showed low institutional trust and limited preparedness, while exposure to flood-hazard maps was associated with improved risk understanding and greater willingness to adopt adaptive measures. These findings highlight the value of combining climate-informed flood-hazard information with community-based risk communication to support adaptive flood-risk management in the basin.

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Integration of Climate-Informed Flood Hazard Modelling and Community Perceptions for Adaptive Flood Risk Management in the Maha Oya River Basin, Sri Lanka



A COMPARATIVE ANALYSIS OF INTER-REGIONAL AIR POLLUTION TRENDS IN SRI LANKA

U.S.N. Wickramasinghe^{1*}, S.M. Imbulana¹, J.M.A. Manatunge¹

¹ Department of Civil Engineering, University of Moratuwa, Moratuwa, Sri Lanka

**Corresponding author: sandaranw@gmail.com*

Abstract

Air pollution is a major environmental and public health concern in Sri Lanka, yet island-wide comparative evidence covering both fine and coarse particulate matter remains limited. This study evaluated spatial and temporal patterns of PM_{2.5} and PM₁₀ using daily observations from twenty National Building Research Organisation monitoring stations from March 2020 to December 2024. Daily rainfall records were available for nine stations and were used to examine the relationship between precipitation and particulate concentrations. Descriptive statistics, annual and seasonal comparisons, Pearson correlation and compliance assessment against World Health Organization guidelines and Sri Lankan national standards were applied. Mean PM_{2.5} concentrations ranged from 15.10 $\mu\text{g}/\text{m}^3$ at Nuwara Eliya to 28.28 $\mu\text{g}/\text{m}^3$ at Badulla, while mean PM₁₀ concentrations ranged from 21.86 $\mu\text{g}/\text{m}^3$ at Nuwara Eliya to 40.11 $\mu\text{g}/\text{m}^3$ at Jaffna. All twenty stations exceeded the World Health Organization annual guidelines for both pollutants, although period-average concentrations remained within the Sri Lankan national annual standards. The lowest annual concentrations occurred in 2021, followed by substantial increases from 2022 onwards. Both pollutants were consistently higher during the northeast monsoon period. Rainfall showed only weak negative-to-negligible relationships with particulate concentrations. The results demonstrate substantial spatial and temporal variability and indicate that regional transport and seasonal atmospheric processes are important considerations for particulate pollution management in Sri Lanka.

Keywords: Inter-station comparison, Monsoon seasonality, NBRI, Particulate matter, Transboundary pollution

1. Introduction

Previous studies have largely concentrated on major urban locations such as Colombo and Kandy, limiting understanding of how particulate pollution varies across the wider country. Studies have also identified the influence of regional atmospheric transport, including the movement of dust and combustion-related pollutants from South Asia into Sri Lanka, particularly during the northeast monsoon [1]. The December 2022 Mandous cyclone further demonstrated the potential for transboundary transport to produce severe particulate pollution episodes in Sri Lanka [4]. At the same time, COVID-19 restrictions provided an unusual period in which reductions in traffic and other human activities could be reflected in measured pollutant concentrations [2].

Despite these developments, a gap remains in systematic island-wide comparison of PM_{2.5} and PM₁₀ using the full available multi-station monitoring network. The present study therefore examines particulate pollution across twenty monitoring stations from March 2020 to December 2024. The analysis focuses on spatial differences between stations, changes through time, monsoon-related seasonality, the relationship between rainfall and particulate concentrations at stations with concurrent meteorological observations, and compliance with health-based and national air quality criteria. The study provides a comparative evidence base for interpreting particulate pollution beyond individual urban centres and for identifying locations that warrant closer monitoring and source-specific investigation.

2. Methodology

Daily mean PM_{2.5} and PM₁₀ concentrations were obtained from the National Building Research Organisation monitoring network for twenty stations distributed across Sri Lanka. The study period extended from March 2020 to December 2024. Data quality control included removal of negative particulate concentrations, review of extreme observations, and retention of valid observations for each station. Stations with shorter observation periods were included in spatial comparisons but were interpreted cautiously when assessing multi-year trends. Rainfall data from the Department of Meteorology were available concurrently for Anuradhapura, Badulla, Colombo, Embilipitiya, Galle, Jaffna, Kurunegala, Monaragala and Ratnapura.

For each station, arithmetic mean, median, standard deviation, minimum, maximum and valid observation counts were calculated. Annual mean concentrations were calculated for each available station-year, and inter-annual changes were compared to describe temporal behaviour. Monthly means were used to examine seasonality in relation to the northeast monsoon, first inter-monsoon, southwest monsoon and second inter-monsoon periods. A seasonal contrast ratio was calculated by comparing northeast monsoon and southwest monsoon means. The PM₁₀-to-PM_{2.5} ratio was also examined as an indicative measure of differences in coarse and fine particulate contributions. These comparative measures were used alongside the statistical summaries to interpret spatial, temporal and seasonal patterns rather than relying on statistical significance alone.

Pearson correlation coefficients were calculated between paired daily rainfall and particulate observations at the nine concurrent stations, with statistical significance assessed at the five percent level. Compliance was evaluated against the World Health Organization 2021 annual and twenty-four-hour guidelines and Sri Lankan National Ambient Air Quality Standards. The percentage of monitored days exceeding the World Health Organization twenty-four-hour guidelines was calculated for both pollutants. Data management and tabulation were conducted using Microsoft Excel and Tableau.

3. Results and Discussion

Marked spatial differences were observed across the monitoring network. Mean PM_{2.5} concentrations ranged from 15.10 micrograms per cubic metre at Nuwara Eliya to 28.28 at Badulla, while mean PM₁₀ ranged from 21.86 at Nuwara Eliya to 40.11 at Jaffna. PM₁₀ exceeded PM_{2.5} at every station. The PM₁₀-to-PM_{2.5} ratio ranged from 1.305 to 1.626, with relatively high ratios at Jaffna and Colombo. Jaffna recorded the largest observed PM₁₀ maximum of 264 micrograms per cubic metre, while the largest PM_{2.5} maximum was 139 micrograms per cubic metre.

All twenty stations exceeded the World Health Organization 2021 annual guidelines of 5 micrograms per cubic metre for PM_{2.5} and 15 micrograms per cubic metre for PM₁₀. Annual PM_{2.5} concentrations were approximately three to six times the guideline, while PM₁₀ was approximately 1.5 to 2.7 times higher. Nevertheless, all stations complied with the Sri Lankan national annual standards on a period-average basis. Daily PM_{2.5} exceedance ranged from 44 percent to 99 percent of monitored days, whereas PM₁₀ exceedance ranged from 2 percent to 30 percent.

The lowest annual concentrations occurred in 2021 at all stations with sufficient multi-year records. Concentrations increased sharply in 2022 and remained elevated through 2023 and 2024. At several stations, the increase from 2021 to 2022 was approximately 58 to 67 percent for PM_{2.5} and 37 to 79 percent for PM₁₀. The strong 2022 increase, particularly at Jaffna and Colombo, is consistent with the transboundary pollution episode associated with the Mandous

cyclone [4]. The 2021 reduction is also consistent with documented decreases in urban pollution during COVID-19 restrictions [2].

Both pollutants were consistently higher during the northeast monsoon from December to March and lower during the southwest monsoon. The strongest contrasts occurred at Jaffna, Colombo and Galle. At Jaffna, the northeast-to-southwest seasonal ratios were approximately 1.9 for PM_{2.5} and 1.6 for PM₁₀, while monthly PM₁₀ reached 57.9 micrograms per cubic metre in December. These patterns are consistent with regional atmospheric transport during the northeast monsoon [1].

Rainfall showed only weak relationships with particulate concentrations. Across the nine concurrent stations, Pearson correlations ranged from minus 0.120 to plus 0.007 for PM_{2.5} and from minus 0.101 to plus 0.019 for PM₁₀. The strongest negative associations occurred at Kurunegala, Monaragala and Ratnapura, while relationships at Jaffna and Galle were close to zero. The strong positive relationship between station-level mean PM_{2.5} and PM₁₀, with a Pearson correlation coefficient of 0.93, indicates shared drivers. Overall, particulate pollution should be interpreted using spatial context, seasonal atmospheric circulation and source characteristics rather than rainfall alone.

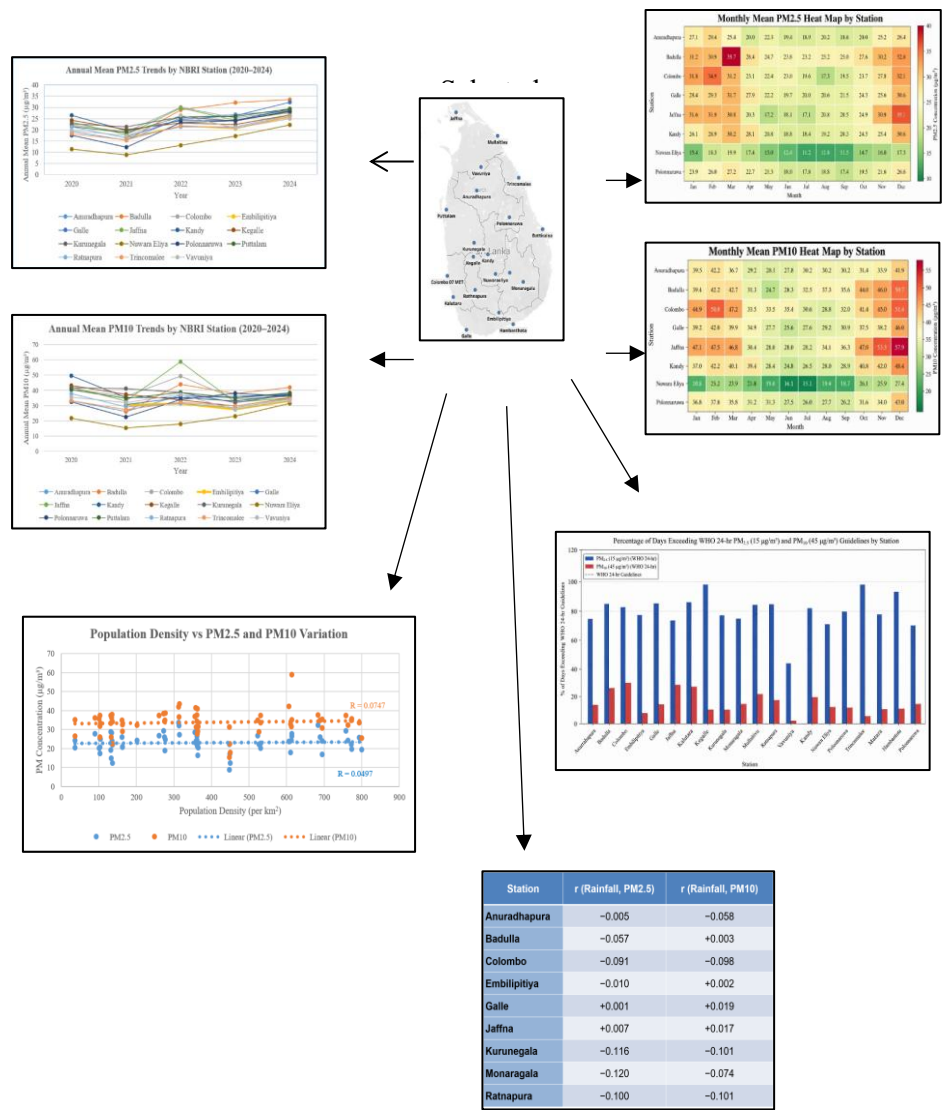
4. Conclusions

The study demonstrates substantial spatial and temporal variability in particulate pollution across Sri Lanka. All twenty monitoring stations exceeded the World Health Organization annual guideline values for both PM_{2.5} and PM₁₀, despite remaining within the current Sri Lankan national annual standards on a period-average basis. The lowest concentrations were observed at Nuwara Eliya, while Badulla had the highest mean PM_{2.5} and Jaffna had the highest mean PM₁₀ and the most pronounced coarse-particle episodes. The common 2021 minimum, subsequent increase from 2022 onwards, and strong northeast monsoon enhancement indicate that particulate pollution is influenced by both changes in human activity and regional atmospheric processes. The weak rainfall correlations show that precipitation alone is insufficient to explain particulate variability.

The findings support continued strengthening of the national monitoring network, improved integration of meteorological observations, and targeted source investigations at stations with distinctive pollution signatures. Future studies should incorporate wind fields, atmospheric transport analysis, chemical composition and source-apportionment methods to distinguish local emissions from transboundary contributions more directly.

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ADVANCING SDG 6 THROUGH INTEGRATED WATER CONSERVATION IN SRI LANKA: A REVIEW-BASED FRAMEWORK AND IMPLEMENTATION PATHWAY

C.N. Edirisinghe^{1*}, J.M.A. Manatunge², S.M. Imbulana³

^{1,2,3} University of Moratuwa, Colombo, Sri Lanka

**Corresponding author: chanuda22@gmail.com*

Abstract

Sri Lanka has several existing water conservation measures, including rainwater harvesting, wastewater reuse, demand-side efficiency, green building provisions and policy instruments. However, these measures are often implemented separately, limiting their collective effectiveness and contribution to Sustainable Development Goal 6. This study examines how existing conservation measures can be better integrated within the Sri Lankan context. A structured review-based qualitative thematic synthesis was conducted using journal articles, Sri Lankan policy documents, technical guidelines, project reports and international best-practice sources, with evidence organised and coded to identify recurring conservation measures, implementation barriers and enabling mechanisms. The thematic synthesis resulted in four themes: water supply, treatment and reuse systems; demand-side water use and end-use efficiency; built environment and design-based strategies; and governance, policy and economic instruments. The synthesis identifies fragmented implementation, institutional coordination gaps, inadequate monitoring and inconsistent user adoption as recurring constraints across the four thematic areas. Based on these findings, a Multi-Layer Water Conservation Framework is proposed to connect policy and governance, infrastructure and design, technology and systems, and user and demand considerations. A phased Implementation Pathway Framework further translates these components into short-, medium- and long-term actions aligned with relevant national SDG 6 targets and water-sector priorities. Together, the frameworks provide a structured basis for moving from isolated conservation measures towards more coordinated water conservation planning in Sri Lanka, thereby supporting progress towards SDG 6.

Keywords: End-use efficiency, Wastewater reuse, Green building strategies, Institutional coordination, Implementation

1. Introduction

Sri Lanka faces water management challenges due to uneven rainfall, groundwater vulnerability, infrastructure losses and limited wastewater reuse. Although several conservation measures are available, they are often implemented separately, while institutional fragmentation further limits effective coordination [1]–[4].

Water conservation is also directly related to Sri Lanka's national priorities under SDG 6. These include improving wastewater treatment, recycling and safe reuse under Target 6.3, increasing water-use efficiency under Target 6.4, advancing integrated water resources management under Target 6.5, and strengthening participation in water and sanitation management under Target 6.b [1]. National water-sector policies further emphasise water conservation, rainwater harvesting, wastewater reuse, monitoring and institutional coordination [2], [3]. These priorities provide an important policy basis for integrating currently fragmented conservation measures.

This study synthesises global and Sri Lankan literature to identify key strategies, implementation gaps and opportunities for better integration across the water sector. The review considers technical, built-environment, behavioural and governance-related measures to understand how they can function as part of a coordinated system. Particular attention is given to the connections between policy, infrastructure, technology and user participation. Based on these findings, a Multi-Layer Water Conservation Framework and an Implementation Pathway Framework are proposed to support coordinated action aligned with Sri Lanka's national SDG 6 and water-sector priorities.

2. Methodology

A structured review-based qualitative thematic synthesis was conducted using journal articles, Sri Lankan policy documents, technical guidelines, project reports and international best-practice sources. Search terms were derived from the study objectives and organised around key concepts including water conservation, rainwater harvesting, wastewater and greywater reuse, non-revenue water, water-use efficiency, demand management, green buildings, water governance and SDG 6. Terms relating to Sri Lanka were incorporated where relevant to identify local evidence, while international sources were reviewed to identify established and potentially transferable practices.

Sources were considered where they provided evidence on conservation measures, implementation mechanisms, governance, user participation or barriers relevant to water conservation. Relevant information was organised in a structured review matrix covering the conservation measure, application context, implementation approach, enabling factors and reported implementation constraints.

Following thematic synthesis principles [5], recurring findings were initially coded and related codes were progressively grouped according to their functional role in water conservation. This iterative grouping resulted in four higher-level themes: water supply, treatment and reuse systems; demand-side water use and end-use efficiency; built environment and design-based strategies; and governance, policy and economic instruments. Issues recurring across multiple themes, particularly integration, institutional coordination, monitoring and user adoption, were identified as cross-cutting findings. International approaches were then compared with Sri Lankan practices to identify implementation gaps and opportunities, which formed the basis for the proposed Multi-Layer Water Conservation Framework and phased Implementation Pathway Framework.

3. Results and Discussion

The synthesis shows that Sri Lanka already has conservation mechanisms across the four thematic areas. Water supply, treatment and reuse measures include rainwater harvesting, wastewater and greywater reuse, reclamation and non-revenue water reduction [2], [3]. Demand-side measures include efficient fittings, metering, water audits, awareness and economic mechanisms intended to influence consumption. Built-environment strategies, including metering, rainwater harvesting and water-efficient design, are also recognised within Sri Lankan green building criteria [4]. Governance and policy mechanisms provide the institutional and regulatory basis for conservation, reuse and coordination [1]–[3].

Across these themes, four recurring implementation issues emerged. First, conservation measures are often implemented as individual interventions rather than as components of an integrated system. Second, responsibilities for water supply, sanitation, buildings and resource management are distributed across different institutions, creating coordination challenges.

Third, monitoring gaps limit the ability to assess water use, system losses and the actual performance of conservation measures. Finally, the effectiveness of demand-side and decentralised measures depends on user adoption, operation and maintenance. The synthesis therefore indicates that Sri Lanka's principal need is stronger integration and coordinated implementation of existing measures rather than reliance on isolated interventions.

3.1 Multi-Layer Water Conservation Framework

The proposed Multi-Layer framework (Figure 1) integrates four interacting layers: Policy and Governance; Infrastructure and Design; Technology and Systems; and User and Demand. Governance provides the regulatory and institutional basis, infrastructure enables physical implementation, technologies support conservation and reuse, and users influence adoption, operation and maintenance.

These layers operate as a feedback system in which governance enables implementation and infrastructure development, infrastructure supports appropriate technologies, and user response and system performance inform subsequent management decisions. The framework therefore provides a mechanism for connecting conservation measures that are otherwise implemented through separate technical and institutional pathways [2], [3].

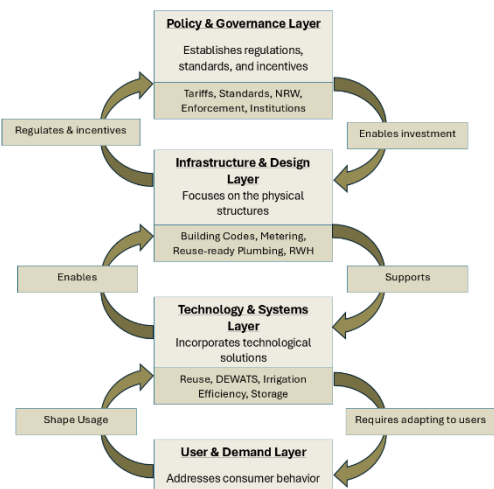


Figure 1: Proposed multi-layer water conservation framework for Sri Lanka.

3.2 Implementation Pathway Framework

The Implementation Pathway (Figure 2) translates the framework into phased actions while relating the proposed measures to Sri Lanka's national SDG 6 and water-sector priorities. Short-term actions focus on strengthening existing mechanisms through rainwater harvesting, awareness, water audits, water-efficient fittings and non-revenue water monitoring. These measures primarily support SDG Target 6.4 on improving water-use efficiency and existing national policy directions on water conservation and rainwater harvesting [1], [2].

Medium-term actions include wider metering, efficiency standards, reuse-ready buildings and fit-for-purpose wastewater reuse. These measures support Targets 6.3 and 6.4 by improving water-use efficiency while increasing opportunities for wastewater treatment, recycling and safe reuse [1], [3].

Long-term actions include advanced reclamation, digital water accounting, basin-scale water management and stronger inter-agency coordination. These actions are consistent with Target 6.5 on integrated water resources management and the broader requirement for coordinated and participatory water management under Target 6.b [1]–[3]. The pathway therefore

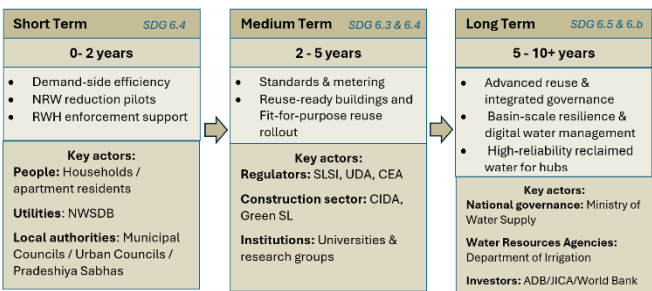


Figure 2: Proposed implementation pathway framework for phased water conservation action in Sri Lanka.

progresses from strengthening existing conservation practices, through institutionalising efficiency and reuse, towards more integrated and data-supported water management.

4. Conclusions

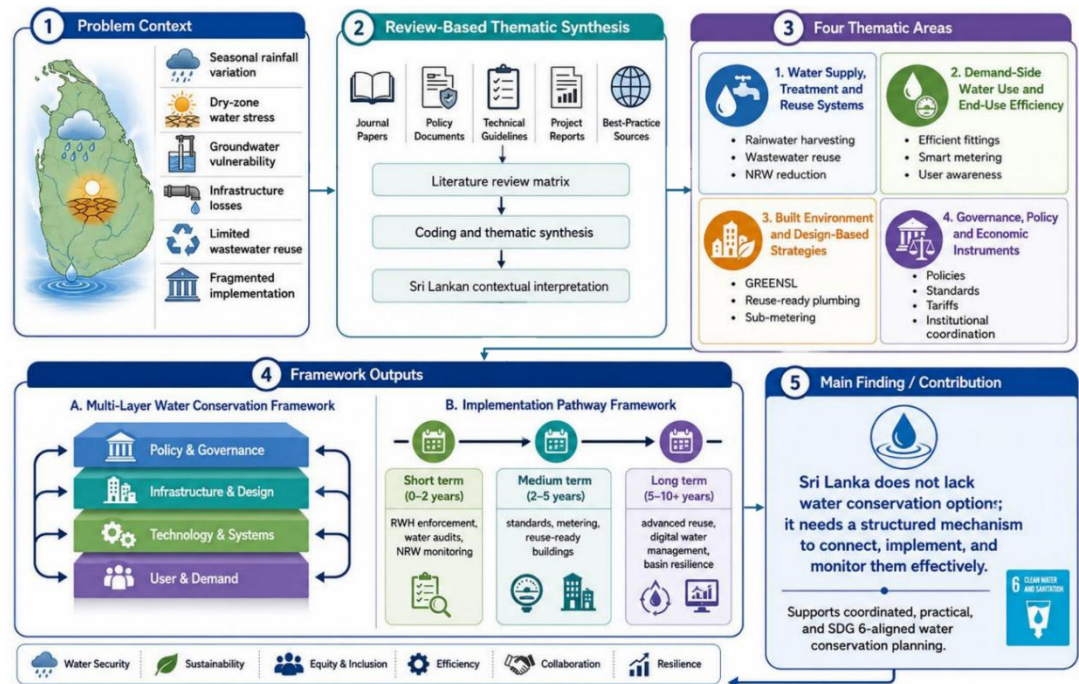
The thematic synthesis shows that Sri Lanka already has several water conservation measures across supply and reuse, demand management, the built environment and governance. However, their effectiveness is constrained by fragmented implementation, institutional coordination and monitoring gaps, and user adoption.

The study therefore proposes a Multi-Layer Water Conservation Framework to connect governance, infrastructure, technology and users, together with a phased Implementation Pathway aligned with relevant national priorities under SDG Targets 6.3, 6.4, 6.5 and 6.b. Together, the frameworks provide a structured basis for progressing from isolated measures towards more coordinated water conservation planning and implementation in Sri Lanka. Future work should focus on stakeholder validation and quantitative assessment of potential water savings.

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Graphical Abstract



DEVELOPING AN EMPIRICAL RELATIONSHIP BETWEEN RAINFALL CHARACTERISTICS AND MICROPLASTIC EMISSIONS IN AN URBAN RIVER

Thavindu Abeysekara^{1*}, Sachithra Imbulana¹

¹ Department of Civil Engineering, University of Moratuwa, Sri Lanka

**Corresponding author: abeysekaratcm.21@uom.lk*

Abstract

Rainfall runoff transports microplastics into urban rivers, but concentration responses vary between events. This study analysed a secondary dataset from the Takano River, Kyoto, Japan, to evaluate river flow as a predictor of microplastic concentration. Records for particles between 10 and 300 micrometres were examined using time series, correlations and regression. Light rainfall produced an early concentration peak, moderate rainfall showed coincident flow and concentration peaks, and heavy rainfall produced delayed peaks during flow recession. A power-law model fitted to the light and moderate events explained 84 percent of the variation in log-transformed particle concentration. Leave-one-out cross-validation gave a coefficient of determination of 0.81. River flow therefore provided a useful predictor within the observed event domain. However, the model estimates total concentration at the monitoring site without separating upstream inputs from local rainfall wash-off. Transfer to other catchments requires validation because land use, surface resistance and microplastic sources can alter transport. Heavy rainfall requires consideration of storage, remobilisation and delayed delivery.

Keywords: Environmental pollution, Stormwater runoff, Hydrological modelling, Particle concentration, First flush

1. Introduction

Urban rivers are important pathways for microplastic transport, particularly during rainfall when runoff mobilises particles accumulated on impervious surfaces and within drainage networks. Event-based studies show pronounced first-flush behaviour and substantial intra-event variability, with transport controlled by rainfall and river hydraulics [1], [2]. High-frequency monitoring is therefore needed to capture short concentration pulses that conventional grab sampling can miss.

Process-based transport models can represent complex mechanisms but often require extensive data and parameterisation. Empirical approaches provide a practical alternative when high-frequency hydrological measurements are available [3]. This study examined particle and mass concentration dynamics under different rainfall magnitudes and assessed whether river flow could serve as a parsimonious predictor, while distinguishing direct wash-off from delayed transport during intense storms.

2. Materials and Methods

A secondary rainfall-runoff dataset from Mikage Bridge on the Takano River, Kyoto, Japan, was analysed [1]. The three monitored events represented light rainfall of 6 mm over 5 h, moderate rainfall of 24 mm over 7 h, and heavy rainfall of 52 mm over 7 h. The dataset contained particle-level observations together with rainfall intensity, river flow, particle characteristics, sample volume, and derived concentrations.

The analysis retained small microplastics from 10 to 300 micrometres and aggregated particle records by sampling time, producing 8, 11, and 14 observations for Events 1, 2, and 3. Time-series plots compared river flow with particle and mass concentration, and Pearson correlation matrices were used to evaluate associations among rainfall, flow, particle count, mass, and concentration indicators.

A power-law flow-concentration model was developed from Events 1 and 2 because both showed comparatively direct wash-off behaviour, whereas Event 3 showed delayed peaks and weaker zero-lag association. River flow and particle concentration were transformed using base-10 logarithms and fitted by linear regression. Validation used leave-one-out cross-validation, 5000-replicate bootstrap confidence intervals for the slope, and Cook's distance. Low-flow, high-flow, and mid-range subsets were also tested to determine whether restricting the flow domain improved the fit. All analyses were completed in RStudio. The regression used river flow as its sole predictor; catchment characteristics, source contributions and upstream-downstream background differences were not quantified separately.

3. Results and Discussion

3.1 Event-Specific Transport Behaviour

Under light rainfall, particle concentration peaked before river flow, consistent with first-flush behaviour [2], while mass concentration peaked closer to the rainfall maximum. Moderate rainfall produced synchronous peaks in rainfall, flow and both concentration measures, supporting a close hydrological association consistent with hydraulic influences on transport [4].

During heavy rainfall, mass and particle concentrations peaked approximately three and four hours after peak flow, respectively. These recession-phase peaks suggest delayed delivery, storage and remobilisation [1], supporting exclusion of this event from the zero-lag calibration.

3.2 Empirical Relationship and Model Validation

Combining Events 1 and 2 produced a strong log-log relationship between river flow and particle concentration. The fitted power-law model was:

$$C_p = 1.02 Q^{5.71}$$

Here, C_p is particle concentration in particles m^{-3} and Q is river discharge in $\text{m}^3 \text{s}^{-1}$. The log-scale coefficient of determination was 0.84. The exponent of 5.71 describes a strongly nonlinear, site-specific response within the observed flow range.

Leave-one-out cross-validation gave a root mean square error of 0.36 and a mean absolute error of 0.26 on the base-10 logarithmic concentration scale, with a cross-validated coefficient of determination of 0.81. The 95 percent bootstrap interval for the slope was 4.848–7.186. Cook's distance flagged influential observations. Independent rainfall events are needed to assess predictive performance beyond this dataset.

Restricting the flow range produced no clear improvement; the complete Event 1 and Event 2 range was retained.

3.3 Catchment Controls and Model Limitations

Catchment land use, impervious cover and slope influence runoff generation and connectivity, while surface roughness alters flow resistance, particle retention and delivery timing [2], [4].

Rougher surfaces may delay wash-off and retain particles; the response also depends on water depth and particle properties [4]. River flow integrates some catchment effects but does not uniquely describe particle availability or retention. Consequently, the same flow can produce different concentrations under different catchment conditions, and both model parameters may require recalibration elsewhere.

Potential urban sources include tyre and road wear, fragmented litter, industrial plastic losses, atmospheric deposition and wastewater-borne fibres. Their relative importance varies with land use, human activity, wastewater management and antecedent dry periods [2], [5]. Changes in source abundance and particle composition can therefore alter the concentration–flow relationship. These are potential contributors; their proportions were not quantified for the analysed samples.

Downstream concentration combines upstream particle inputs with local wash-off and other discharges, modified by dilution, retention and remobilisation. It therefore need not increase downstream. A high background load can obscure the relative rainfall signal, while dilution can reduce concentration even when particle flux increases. Since particle flux is the product of flow and concentration, concentration differences alone cannot quantify newly washed-off loads. Separating these components requires concurrent flow measurements and upstream–downstream sampling that accounts for travel time. The fitted model predicts total concentration at Mikage Bridge, not the additional load generated solely by rainfall wash-off.

4. Conclusions

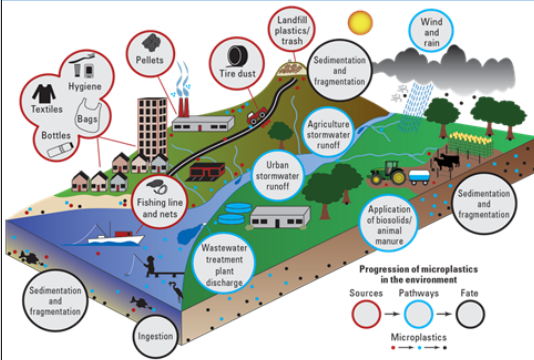
The light and moderate events supported a flow-based model with a log-scale coefficient of determination of 0.84, whereas the heavy event showed delayed concentration peaks. The model predicts total particle concentration under the observed site and event conditions. Catchment properties, source variability and upstream background inputs limit its transferability and the attribution of concentrations to new rainfall wash-off. Further development requires additional events, catchment and source information, and concurrent upstream–downstream monitoring.

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Developing an empirical relationship between rainfall characteristics and microplastic emissions in an urban river

MP transport pathways



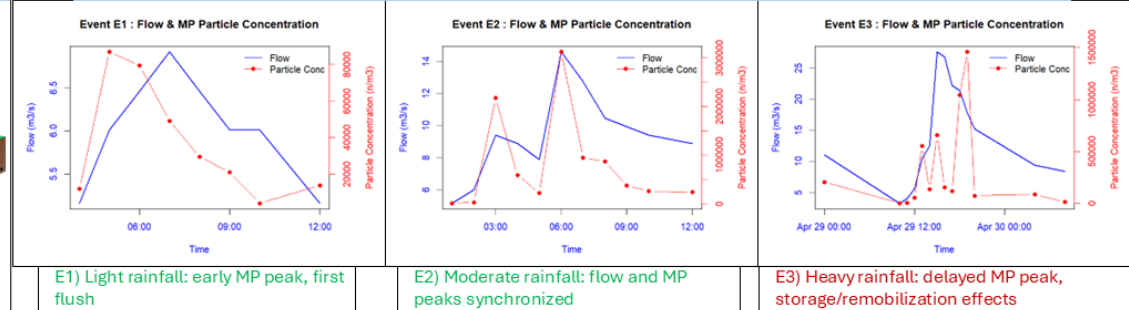
Rainfall mobilizes urban microplastics
Urban surfaces → Stormwater drains → River
MPs enter the river during runoff

Rainfall – MP emissions dataset

Takano River, Kyoto, Japan
3 rainfall events → Light, Moderate, Heavy
Variables: River flow, MP concentration
Analysis using R programming

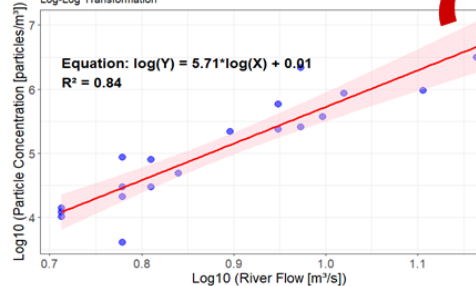


Event specific MP behavior



Empirical prediction model

Flow vs. Mp concentration (Events 1 & 2)
Log-Log Transformation



$$C_p = 1.02Q^{5.71}$$

$R^2 = 0.84$
Events 1 & 2 combined
Event 3 was removed

Validation methods
Leave-one-out cross-validation
Bootstrap confidence interval on the slope
Cook's distance analysis

River flow is a strong predictor under light-to-moderate rainfall
Heavy rainfall requires more complex modelling

ASSESSING THE EFFECTS OF CONSECUTIVE EXTREME RAINFALL EVENTS UNDER FUTURE CLIMATE SCENARIOS ON RESERVOIR STORAGE AND SPILLWAY REQUIREMENTS: A CASE STUDY OF MANANKATTIYA RESERVOIR, SRI LANKA

Jayani Malwattegedara^{1*}, Luminda Gunawardhana¹, Lalith Rajapakse¹

¹ Department of Civil Engineering, University of Moratuwa, Sri Lanka

**Corresponding author: malwattegedarammjr.26@uom.lk*

Abstract

Irrigation reservoirs in the dry zone of Sri Lanka are designed for a single design flood, so the damaging condition arises when a second heavy storm arrives while the reservoir is still full. This study examines how consecutive extreme rainfall events change under future climate scenarios and affect the storage and spillway of Manankattiya Reservoir. Daily observed rainfall from 1994 to 2024 generated 12 projection series from three global climate models, under two shared socioeconomic pathways and two future periods, giving 60 model-years per scenario; as record lengths differ, counts are compared as events per year. An extreme event was defined by a 200 mm event depth and a compound event by two extremes less than seven days apart. Of 50 compound events identified, 22 were routed through a HEC-HMS rainfall-runoff model. By 2081-2100, compound events become over four times more frequent under the high-emission pathway, rising from 0.06 to 0.30 events per year, and the share of storms qualifying as extreme rises from 3.2% to 8.3%. Each event delivers 25 to 47 million cubic metres (MCM) to a reservoir holding 6 MCM at full supply, and a crest length near 24 m is indicated to keep the peak level below the bund top. As the routing uses daily rainfall for a catchment with a 185-minute lag and a derived elevation-storage relationship, this is a screening value requiring confirmation against the probable maximum flood. Reservoir safety and spillway design must therefore account for consecutive extremes rather than a single design flood.

Keywords: CMIP6 projections, Compound hydrological events, Flood risk management, Reservoir capacity, Spillway crest length

1. Introduction

In seasonally dry regions, the water stored or released during a storm depends mainly on reservoir capacity. Analysis of 178 Indian reservoirs found that flood mitigation depends mainly on antecedent storage, and compound events combining high inflow with a nearly full reservoir may roughly double under warming [1]. Extreme precipitation on consecutive days is also increasing worldwide in observations and model simulations [2]. As storage and spillways are sized from a single design flood, successive extremes are treated as independent and compound events are rarely considered.

This concern is critical in the Sri Lankan dry zone, where a cascade of tanks meets the regional water demand and a reservoir may serve a whole command area. Manankattiya Reservoir, a major tank in the Malwathu Oya basin, drains 61.9 km², holds 6 MCM at a full supply level of 136.30 m, and has a bund top level of 138.71 m. This study assesses how compound rainfall events may change under future climate and their implications for reservoir storage and spillway capacity, conventionally verified against the probable maximum flood.

2. Methodology

Daily observed rainfall from the Huruluwewa gauge from 1994 to 2024 (31 years), with no missing records, drove 12 projection series from the LARS-WG stochastic weather generator [3] using the CNRM-CM6-1, HadGEM3-GC1-LL and MRI-ESM2-0 models under SSP2-4.5 and SSP5-8.5 pathways for 2041 to 2060 and 2081 to 2100, giving 60 model-years per pathway and period, so that records of unequal length are compared as events per year. LARS-WG preserves the inter-event gaps and extreme depths that compound-event identification depends on, scaled by each model and emission scenario [3].

A day with 1.0 mm or more of rainfall was treated as wet, a single dry day ended a storm, and an event was an unbroken run of wet days [2]. A fixed threshold of 200 mm in event depth defined extreme events, preferred over a per-dataset percentile to keep models comparable [4]. It sits above the observed 95th percentile (158.4 mm) and below the model values, so no dataset is dominated. A compound event is two extreme events separated by fewer than 7 days. Each was extracted into a fixed 28-day window starting one dry day before the first storm, with unrelated later storms zeroed. The two largest combined rainfall events per series were carried forward, giving 22 runs. Losses used the SCS curve number method (CN 81) and the SCS unit hydrograph transform (lag 185 minutes). The reservoir was routed as a level pool with an ungated broad-crested spillway at full supply level, using an elevation-storage relationship derived from contour data rather than a bathymetric survey, which affects the computed peak level. The minimum crest length, the shortest length keeping the peak level below the bund top, is a screening value, since the 185-minute lag is short relative to the daily rainfall input.

3. Results and Discussion

The screening found 50 compound events, 48 across the 60 model-years of the ensembles and 2 in the 31-year observed record (0.06 per year). Two series, CNRM-CM6-1 under both pathways for 2041–2060, contained no compound events. The largest observed compound event, in December 2010 to January 2011, caused the most damaging flood, supporting the screening rule.

Table 1 compares projections with the observed baseline: compound events rise from 0.06 per year observed (2 in 31 years) to 0.15 and 0.13 at mid-century and to 0.22 and 0.30 by 2081–2100 under the moderate and high pathways, from counts of 9, 8, 13 and 18 in 60 model-years: a twofold rise at mid-century and up to 4.6-fold by the end of the century. The share of storms qualifying as extreme rises from 3.2% to 8.3%.

Table 1: Summary of extreme and compound events for different scenarios. Observed record 31 years, each scenario 60 model-years; bracketed values are events per year.

Pathway and Period	No. of Extreme Events (per year)	No. of Compound Events (per year)	Inflow Volume (MCM)	Minimum Spillway Length (m)
Observed 1994–2024	30 (0.97)	2 (0.06)	25.7–35.5	13–19
SSP2-4.5 2041–2060	106 (1.77)	9 (0.15)	25.9–46.1	14–24
SSP2-4.5 2081–2100	121 (2.02)	13 (0.22)	25.5–46.0	15–24
SSP5-8.5 2041–2060	102 (1.70)	8 (0.13)	32.1–44.5	16–17
SSP5-8.5 2081–2100	144 (2.40)	18 (0.30)	31.1–46.7	16–20

Figure 1 shows the modelled inflow hydrographs. Inflow volume ranges from 25.5 to 46.7 MCM against 6.02 MCM at full supply, 4.2 to 7.8 times the storage. Daily rainfall was used throughout to compare scenarios against a common baseline. This limits spillway sizing: with

a lag of only 185 minutes, daily rainfall cannot resolve the within-day distribution that governs peak discharge, so the crest lengths in Table 1 show relative differences between scenarios rather than design values. The storage-area relationship was likewise derived rather than surveyed. A design assessment would need sub-daily rainfall, a surveyed elevation-storage relationship and comparison against the capacity required by the probable maximum flood, which normally governs major tank sizing and would exceed the floods reported here.

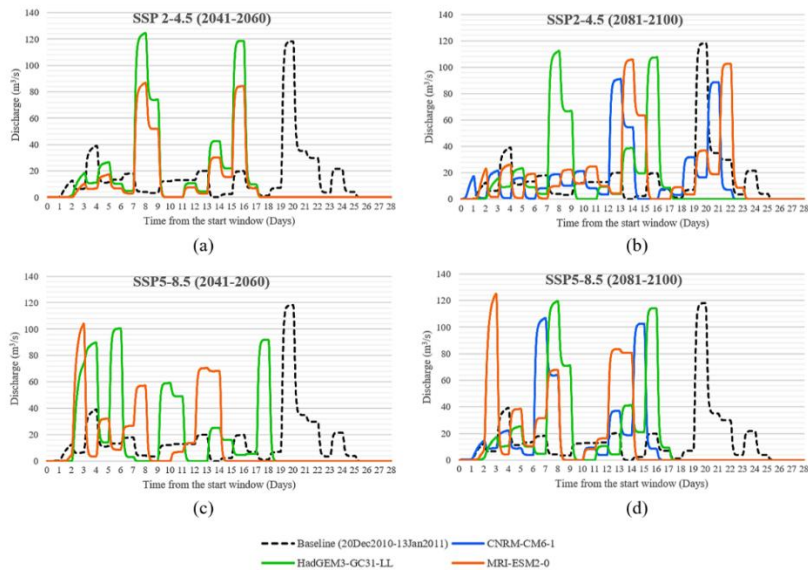


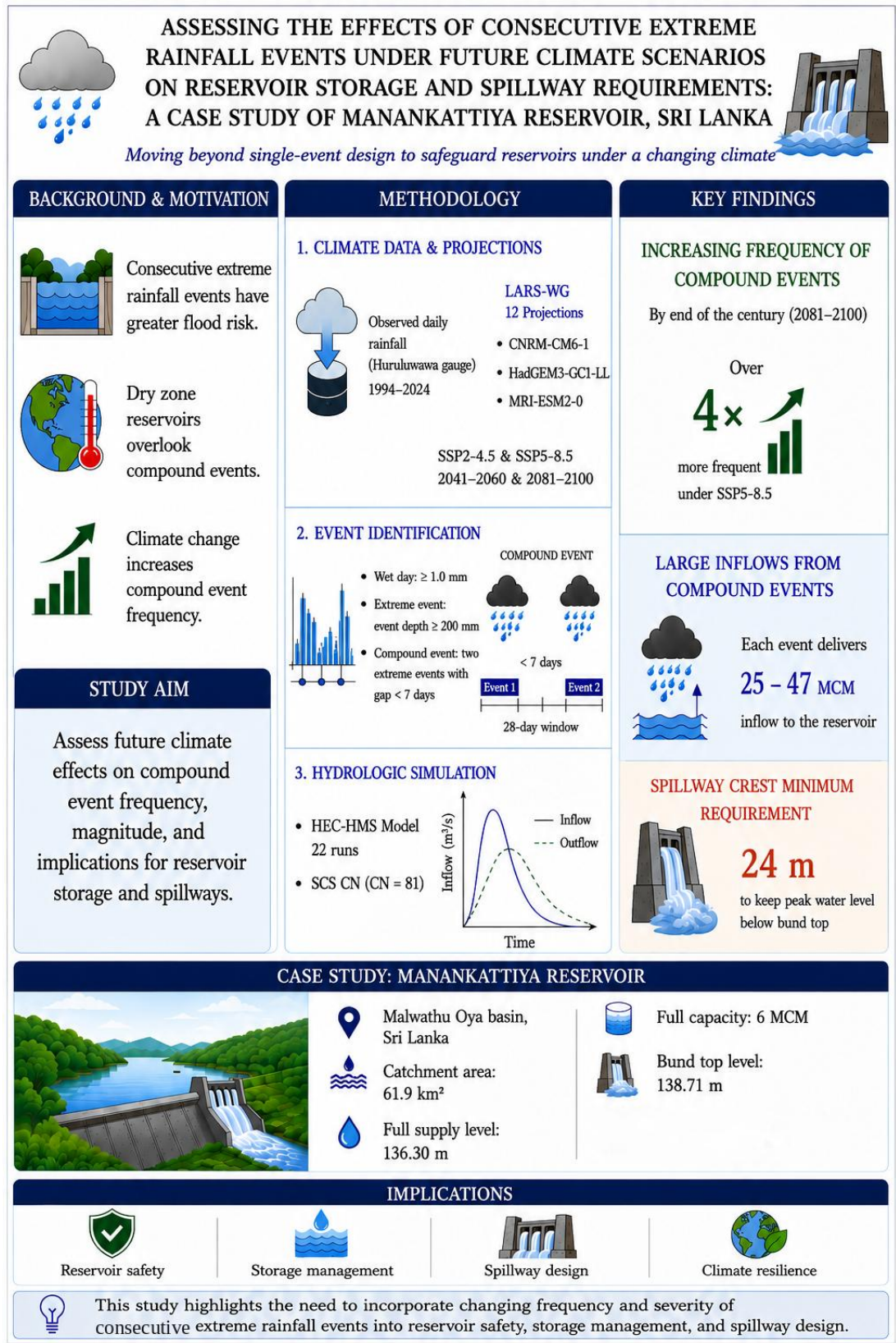
Figure 1: Reservoir inflow hydrographs for (a) SSP2-4.5 2041–2060, (b) SSP2-4.5 2081–2100, (c) SSP5-8.5 2041–2060 and (d) SSP5-8.5 2081–2100.

4. Conclusion

Consecutive extreme rainfall events at Manankattiya become more frequent and moderately more severe under both pathways and most markedly under the high-emission pathway late in the century, where compound events reach 0.30 per year (18 in 60 model-years) against 0.06 per year observed (2 in 31 years), a 4.6-fold rise. Because a single event delivers 25 to 47 MCM, 4 to 8 times the 6 MCM storage, added capacity alone cannot absorb it and a larger spillway crest, of the order of 24 m, is indicated at screening level. This value must be checked against the probable maximum flood, with sub-daily rainfall and a surveyed elevation-storage relationship, before design. Adaptation should also address refill frequency within a season and freeboard when the second storm arrives.

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EVALUATING PROBABILITY DISTRIBUTIONS FOR DESIGN RAINFALL ESTIMATION AND THEIR IMPLICATIONS FOR SPILLWAY DESIGN AT THE KALANKUTTIYA RESERVOIR, MAHAWELI SYSTEM H, SRI LANKA

A.R.L.S. Alahakoon^{1*}, N. Wijayaratna¹, L. Gunawardhana¹

¹ UMCSAWM, Department of Civil Engineering, University of Moratuwa, Sri Lanka

**Corresponding author: alahakoonarls.26@uom.lk*

Abstract

The design of hydraulic structures depends critically on the design flood, which is governed by the choice of probability distribution used to estimate extreme design rainfall. This study evaluates how distribution and estimation method affect design rainfall, design flood, and spillway capacity for the Kalankuttiya Reservoir catchment, Mahaweli System H, Sri Lanka. The Siyambalangamuwa station's annual maximum daily rainfall for 31 years was fitted to six distributions: Gumbel, Generalised Extreme Value, Log-Pearson Type III, Lognormal, Gamma, and Weibull. Anderson-Darling, Kolmogorov-Smirnov, and Chi-square tests were used to evaluate goodness-of-fit. The tail-sensitive Anderson-Darling statistic indicated that Log-Pearson Type III was the best-performing distribution. Design rainfall at the 50-year return period was estimated for each distribution and used to generate design flood hydrographs in a HEC-HMS model. Resulting peak discharge ranged from 230.8 to 293.1 m³/s, corresponding to a required spillway length of 45 to 59 m, a spread of approximately 24 and 27 percent, respectively. Critically, independent of distribution selection, all six distributions show a necessary spillway length that is significantly longer than the current 18 m spillway, indicating a significant capacity deficiency. Log-Pearson Type III is recommended as the primary design basis, with the full distributional range reported as an uncertainty envelope to inform urgent spillway capacity review.

Keywords: Design rainfall, Flood frequency analysis, Probability distributions, HEC-HMS, Spillway capacity

1. Introduction

Reliable estimation of the design flood is essential for safe spillway design, as the spillway is the main protection against dam overtopping and downstream flooding. Design floods are estimated by fitting a probability distribution to observed extreme rainfall data and estimating rainfall for the required return period [2]. However, no single distribution is suitable for all cases, and different distributions fitted to the same data can produce significantly different design rainfall and spillway requirements [1]. This uncertainty is often overlooked when a distribution is selected without proper justification. The Kalankuttiya Reservoir, located in Mahaweli System H, Galnewa DS, Anuradhapura District, has a 53 km² catchment and provides water mainly for irrigation and other downstream needs. The existing spillway is 18 m long. The objective of this study is to identify the most suitable probability distribution for estimating design rainfall in the Kalankuttiya catchment by evaluating six probability distributions using formal goodness-of-fit tests, and to assess the associated uncertainty in the 50-year design flood peak discharge and required spillway length.

2. Methodology

Annual maximum daily rainfall from 1985 to 2015 at the Siyambalangamuwa station, gap-filled using the neighbouring Kalawewa_dam station, was fitted to six distributions: Gumbel, Generalised Extreme Value (GEV), Log-Pearson Type III, Lognormal, Gamma, and Weibull. Gumbel, Lognormal, Gamma, and Log-Pearson III parameters were estimated by the method of moments (frequency-factor approach), consistent with Bulletin 17C practice [3]; GEV and Weibull were estimated by maximum likelihood. Goodness-of-fit was evaluated using the Anderson-Darling (AD), Kolmogorov-Smirnov (KS), and Chi-square tests [2]; the tail-sensitive AD test was prioritised for distribution selection given its relevance to extreme design events.

The 50-year return period was used as the design limit for this study, and the design rainfall was estimated for each distribution. Design flood hydrographs were produced by feeding the generated design storms into a HEC-HMS rainfall-runoff model developed for the Kalankuttiya Basin. River discharge from each hydrograph was routed through the reservoir to determine the spillway length required to safely convey the design flood, directly measuring how distributional choice propagates into spillway capacity uncertainty.

3. Results and Discussion

All six distributions gave statistically acceptable fits ($p > 0.05$, all tests), reflecting the limited power of a 31-year time series to discriminate between candidates (Table 1). Log-Pearson III recorded the lowest Anderson-Darling statistic (0.278), narrowly ahead of Gamma (0.279), and was adopted as the primary design distribution; Gumbel and Lognormal performed best on the less tail-sensitive KS and Chi-square tests.

Table 1: Goodness-of-fit test results for six candidate distributions.

Distribution	KSD	AD statistic	Chi ²	Avg. Rank
Log-Pearson III	0.098	0.278	2.371	2.67
Gamma	0.087	0.279	2.384	2.33
Gumbel	0.091	0.297	2.366	2.33
Lognormal	0.093	0.302	2.309	2.67
GEV	0.114	0.321	2.605	5.00
Weibull	0.120	0.647	3.907	6.00

Figure 1 shows design rainfall by distribution across return periods 2–200 years. All distributions converge below 10 years but diverge substantially at longer return periods relevant to spillway design, with Weibull and GEV trending highest and Gamma and Lognormal lowest.

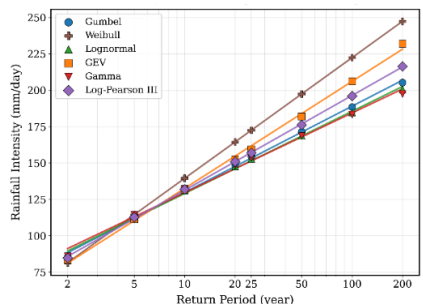


Figure 1: Design rainfall intensity vs return period.

Figure 2 presents the $T = 50$ -year design flood and spillway results. Peak discharge ranged from 230.8 m^3/s (Gamma) to 293.1 m^3/s (Weibull), and required spillway length from 45 to 59 m, a spread of $\sim 24\%$ and $\sim 27\%$ of the mean, respectively. Using Log-Pearson III, required spillway length is 52 m. Furthermore, all six distributions show a capacity deficit of 27–41 m, regardless of which distribution is chosen. This finding is robust to distributional uncertainty and indicates an urgent need for spillway capacity review at Kalankuttiya because the current spillway is only 18 m long.

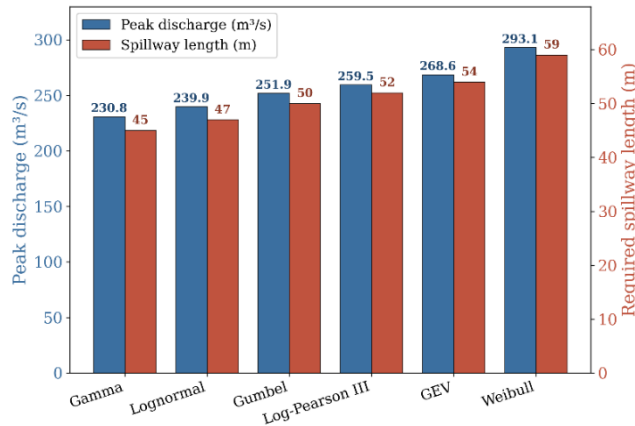


Figure 2: Peak discharge and required spillway length by distribution.

4. Conclusion

For the Kalankuttiya catchment, the choice of distribution was a major, measurable source of uncertainty in the design flood and spillway capacity, resulting in a 24–27% variation in peak discharge and spillway length at $T = 50$ years. More critically, the existing 18 m spillway falls short of the required 45–59 m under every distribution tested, indicating a capacity deficit that is robust to distributional uncertainty and warrants urgent engineering attention regardless of which distribution is ultimately adopted. Log-Pearson III is recommended as the primary design basis given its Anderson-Darling performance, but the full distributional range should inform the capacity review as an explicit uncertainty envelope. Future research can evaluate sensitivity to future land use and climate change, extend the rainfall record, and employ a peaks-over-threshold series to incorporate the Generalised Pareto Distribution.

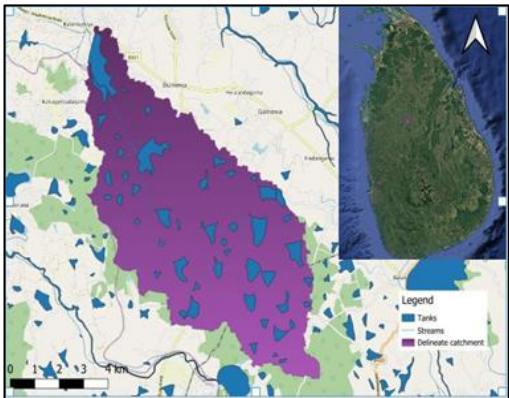
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Distributional Uncertainty in Design Rainfall Reveals a Critical Spillway Capacity Deficit at Kalankuttiya Reservoir, Mahaweli System H, Sri Lanka

53 km ²	31 year	6	45–59 m
Catchment area	Rainfall record used	Distributions compared	Required spillway (vs 18 m existing)

STUDY AREA



Delineated catchment (53 km²) with tank network, Kalankuttiya, Mahaweli System H

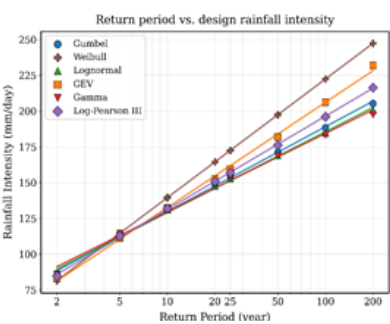


Catchment area: 53 km²
Existing spillway: 18 m long
Rainfall record: 31-yr annual maximum daily rainfall, Siyambalangamuwa rainfall station

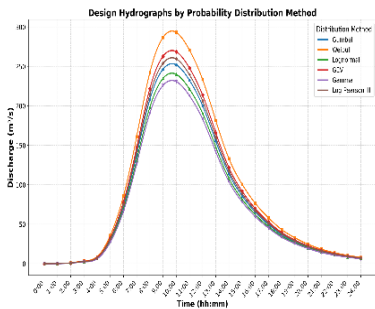
METHOD



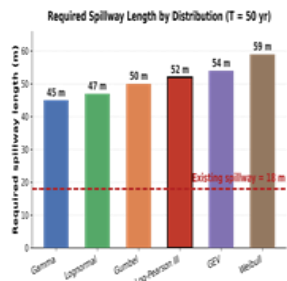
RESULTS



Design rainfall vs. return period, by distribution



Design hydrographs (T = 50 years), by distribution



Required spillway length vs. existing 18 m spillway

- T = 50-year flood: Q = 230.8–293.1 m³/s
- Required spillway length: 45–59 m
- Existing spillway: 18 m
- Capacity gap: 27–41 m
- Design basis: Log-Pearson III

ASSESSING DESIGN HYDROGRAPH AND SPILLWAY CAPACITY SENSITIVITY TO ANTECEDENT SOIL MOISTURE CONDITIONS, RAINFALL PATTERNS AND HYDROLOGICAL TRANSFORMATION UNCERTAINTY IN THE KNUCKLES BASIN

R.L.M.L. Rajasekara¹, K.D. Silva¹, R.L.H.L. Rajapakse^{1*}

¹ UMCSAWM, Department of Civil Engineering, University of Moratuwa 10400, Sri Lanka

**Corresponding author: lalith@uom.lk*

Abstract

Reservoir operation under extreme events requires reliable estimation of design floods while accounting for uncertainties in catchment runoff generation and rainfall temporal distribution. This study evaluates the flood response and capacity adequacy of the Maminiyawa Reservoir, Sri Lanka, using a scenario-based HEC-HMS modelling approach. A 50-year return period design storm was developed, and multiple hydrological scenarios were generated by systematically varying key runoff transformation parameters (Curve Number and the Peak Rate Factor) and rainfall temporal patterns representing front-loaded, centrally loaded, and back-loaded storms. Peak discharge, reservoir pool elevation, and routing response were evaluated to identify the critical condition. Peak discharge ranged from 196.5 to 372.9 m³/s, representing an 89.8% variation among the scenarios. Variations in runoff transformation parameters produced increases of up to 24.8% in peak discharge, while rainfall temporal distribution had a comparatively smaller influence, with a maximum increase of 14.5% for the back-loaded pattern relative to the front-loaded pattern. The critical scenario produced a peak discharge of 372.9 m³/s and a pool elevation of 140.2 m. With a full supply level of 137 m and a bund level of 140 m, the simulated water level exceeded the bund by 0.2 m, indicating potential overtopping under the 50-year design event. The findings demonstrate that explicitly accounting for uncertainty in hydrological transformation and rainfall temporal distribution is important for robust reservoir flood-safety assessment and capacity enhancement planning.

Keywords: Hydrological modelling, Extreme rainfall, Runoff generation, Reservoir routing

1. Introduction

Reliable design flow estimation is fundamental to reservoir safety and spillway design. The design flow estimation is subject to uncertainties associated with rainfall characteristics, land use, runoff generation, and rainfall-runoff transformation. Previous studies have shown that uncertainty in rainfall inputs and hydrological model parameters can substantially affect simulated flood response, while the temporal distribution of rainfall can influence flood magnitude and timing even when the total storm rainfall remains unchanged [1]. Despite the importance of these uncertainties, their combined influence on design floods and reservoir spillway response remains insufficiently investigated in Sri Lankan catchments. In particular, limited attention has been given to how variations in runoff generation, rainfall temporal distribution, and hydrological transformation interact to influence the flood response of existing reservoirs. Therefore, this study aims to evaluate the sensitivity of design floods and spillway capacity to land-use-related runoff generation, rainfall temporal pattern, and

hydrological transformation uncertainty in the Knuckles Basin, using Maminiyawa Reservoir as a case study.

2. Study Area

The study was conducted in the Maminiyawa Reservoir-based cascade system, located within the Knuckles Basin of Sri Lanka. Maminiyawa Reservoir has a storage capacity of 1.8 million m^3 at full supply level and an irrigable extent of approximately 188 ha [2]. The contributing catchment considered in this study covers approximately 23.39 km^2 , with an average basin slope of approximately 4.27%.

3. Methodology

Daily rainfall data from the nearest rain gauge station, Maradankadawala, were used for the analysis. Extreme rainfall was estimated using Weibull and Gumbel distributions, with the Weibull distribution selected based on the higher estimated extreme rainfall. QGIS 3.44.11 was used for land use classification, Curve Number estimation and development of the reservoir area elevation curve using a 30 m $\times$ 30 m digital elevation model (DEM). The absence of hourly rainfall observations required daily rainfall to be disaggregated into hourly data using the temporal disaggregation method, while the 30 m DEM resolution introduced additional uncertainty in the area-elevation relationships. The baseline Curve Number (CN_2) was 78, while $CN_1 = 61$ and $CN_3 = 90$ were derived using NRCS conversion relationships [3]. Rainfall-runoff simulations were performed using HEC-HMS 4.13. Three peak rate factors (PRF): 300, 484, and 600, and three rainfall temporal patterns (front-loaded, centrally peaked, and back-loaded) were considered based on the HEC-HMS Technical Reference Manual [4]. PRF represents the hydrological transformation of excess rainfall into runoff and influences the magnitude and timing of the peak discharge. The combinations of three CN values, three PRFs and three rainfall patterns resulted in 27 simulation scenarios, which were compared to assess this influence on design flood response.

4. Results and Discussion

The 27 HEC-HMS simulations demonstrate that CN, PRF, and rainfall temporal distribution collectively influence the reservoir flood response. Peak discharge varied from 196.5 to 372.9 m^3/s , corresponding to an 89.8% variation across the scenarios. Uncertainty in CN and PRF produced pronounced effects on peak discharge, with increases of 21.7% and 24.8%, respectively, under controlled comparisons. The rainfall temporal pattern produced a comparatively smaller but significant influence, with the maximum difference between back-loaded and front-loaded patterns reaching 14.5%. The critical condition occurred at $CN = 90$ and $PRF = 600$, where the centrally and back-loaded patterns produced the maximum peak discharge of 372.9 m^3/s and a pool elevation of 140.2 m. Figure 2 shows selected outflow hydrographs, with the critical scenario exceeding the 140 m bund level by 0.2 m.

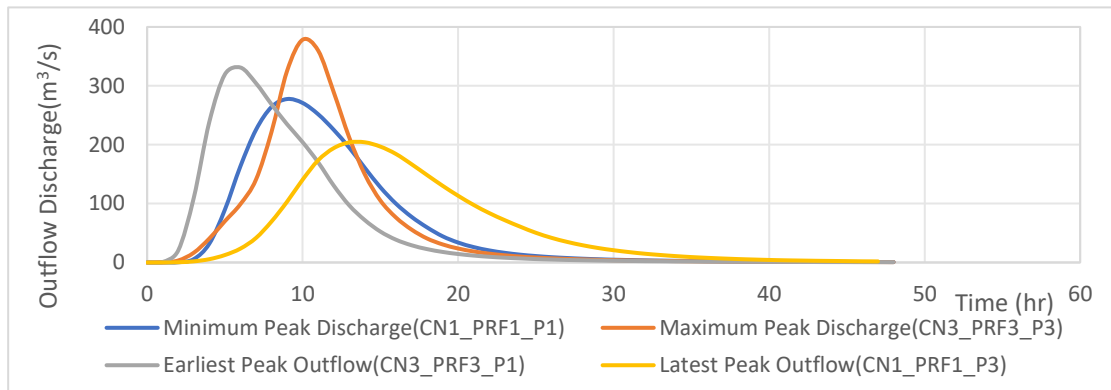


Figure 2: Representative reservoir outflow hydrograph (CN1 = 61, CN3 = 90, PRF1 = 300, PRF3 = 600, P1 = front-loaded pattern, P3 = back-loaded pattern).

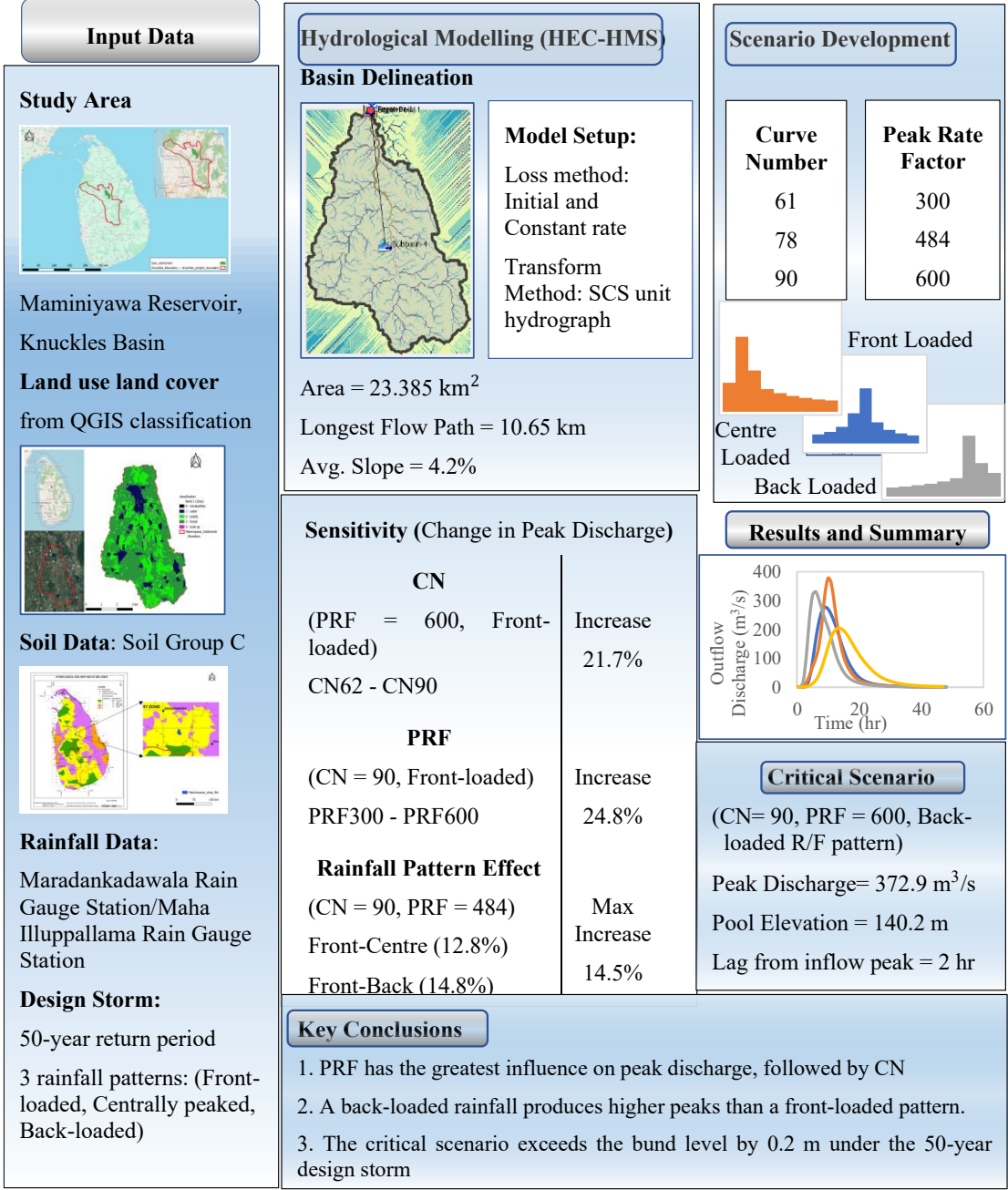
5. Conclusion

The results demonstrate that uncertainty in the Curve Number (CN), peak rate factor (PRF), and rainfall temporal pattern can substantially influence the estimated design flood and reservoir response. Among these factors, CN and PRF introduced the greatest uncertainty in peak discharge, while rainfall temporal distribution had a comparatively smaller but still significant influence. The 27 simulation scenarios resulted in an 89.8% variation in peak discharge, highlighting the importance of explicitly accounting for hydrological transformation and catchment-condition uncertainties in design flood estimation. The critical design condition occurred under the combination of high CN, high PRF, and centrally or back-loaded rainfall. These findings emphasise the need to consider parameter and rainfall-pattern uncertainty when selecting design floods and assessing spillway capacity, rather than relying on a single deterministic hydrological transformation scenario.

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Assessing Design Hydrograph and Spillway Capacity Sensitivity to Antecedent Soil Moisture Conditions, Rainfall Patterns and Hydrological Transformation Uncertainty in the Knuckles Basin



SUSTAINABLE SPOT TREATMENT FOR SRI LANKA'S HIGHWAY CURVES

H.V. Thenuwara^{1*}

¹ Department of Technology/University College of Batangala/University of Vocational Technology,
Sri Lanka

**Corresponding author: hirushivt@gmail.com*

Abstract

Sri Lanka records nearly 38,000 road crashes annually, causing over 3,000 deaths and 8,000 serious injuries, with losses equal to 3 to 5 percent of national gross domestic product (GDP). Roughly 45 percent of fatal and grievous crashes occur where excessive speed meets hazardous horizontal curves in the central highlands, yet existing safety measures rely mainly on driver-behaviour campaigns and civil works rather than pavement friction restoration. This study examines whether locally sourced aggregate can support High Friction Surface Treatment (HFST) as an affordable, low-carbon spot treatment for such curves, reducing dependence on imported bauxite and proprietary resins. Local quarry samples were tested against UK and AASHTO aggregate specifications, and three resurfacing options, hot-mix asphalt overlay, double bituminous surface treatment, and polymer-resin HFST, were compared using a ten-year Life-Cycle Assessment and Life-Cycle Cost Analysis. Quarry sources from Kandy and Anuradhapura met required friction and durability thresholds. HFST produced the lowest ten-year carbon footprint, despite a higher initial cost, and offered wet-weather crash reduction of 60–83% versus 15–25% for conventional treatment, with service life exceeding ten years. These results empirically indicate that domestically manufactured HFST, applied selectively at high-risk curves, offers a durable, economical, environmentally favourable safety solution for Sri Lanka's mountainous highway network, further warranting pilot-scale field trials on system-level performance.

Keywords: Highway crashes, Pavement friction, High friction surface treatment, Horizontal curves, Life-cycle assessment

1. Introduction

Road traffic collisions remain one of Sri Lanka's most persistent public-safety and economic burdens. The country records approximately 38,000 crashes each year, resulting in more than 3,000 deaths and 8,000 serious injuries, with direct and indirect losses estimated at 3–5% of national Gross Domestic Product (GDP) [1]. A substantial share of this toll originates in the hill country, where narrow, winding alignments force drivers to negotiate tight horizontal curves. Excessive approach speed combined with unfavourable curve geometry is implicated in nearly 45% of fatal and grievous crashes nationwide [2].

National road-safety programmes have historically emphasised driver-behaviour campaigns and conventional civil works: widening the carriageway, improving sight distance, or installing speed-calming humps. Yet, international pavement-engineering evidence points to a more direct lever: restoring skid resistance at the tyre–pavement interface. High Friction Surface Treatment (HFST), in which a thin epoxy or polyester-resin binder locks a highly angular, polish-resistant aggregate onto the wearing course, has been shown to cut curve-related crashes by 50–100% in mature road networks abroad, while lasting 7–15 years and returning a favourable benefit-cost ratio [3,4].

The barrier to adopting HFST locally is not its performance but its supply chain: specification-grade aggregates such as calcined bauxite, and the proprietary resins paired with them, are almost entirely imported, which inflates first cost and undermines sustainability. This study therefore investigates whether aggregate sourced from domestic quarries can substitute for imported material in a curve-specific (point-of-curvature to point-of-tangent) spot treatment, offering upcountry Sri Lanka a safety intervention that is simultaneously affordable, durable, and low-carbon.

2. Research Objectives and Methodology

The study set out to characterise candidate Sri Lankan quarry aggregates against internationally recognised HFST specifications, and benchmark a locally sourced HFST against two conventional resurfacing treatments: a Hot-Mix Asphalt (HMA) overlay and a Double Bituminous Surface Treatment (DBST), through a combined Life-Cycle Assessment (LCA) and Life-Cycle Cost Analysis (LCCA), so that the environmental and financial trade-offs of each option could be compared on equal terms.

Rock samples were collected from quarries in the Colombo, Kurunegala, Kalutara, Anuradhapura and Kandy districts and tested for Polished Stone Value (PSV), Sodium-Sulphate Soundness (SSS), Los Angeles Abrasion Resistance (LAAB), and moisture content, following the United Kingdom (UK) Design Manual for Roads and Bridges and the AASHTO HFST aggregate criteria [3]. In parallel, a cradle-to-gate-plus-use-phase LCA was built in accordance with ISO 14040/14044 for a 1 m² functional unit over a 10-year analysis period, comparing a 40-mm HMA overlay (96.0 kg/m² aggregate, 4.8 kg/m² binder), a two-cycle DBST/emulsion treatment (40.0 kg/m² aggregate, 4.0 kg/m² emulsion, 5-year cycle life), and a polymer-resin HFST using the local aggregate (8.0 kg/m² aggregate, 1.45 kg/m² epoxy resin, 10-year life) [4]. A parallel 10-year present-value LCCA, discounted at a 4% real rate, captured initial construction cost together with scheduled maintenance for each option.

3. Results and Analysis

Anuradhapura and Kandy quarry sources met the target specification for low-to-medium-volume rural highways. Anuradhapura aggregate returned a Polished Stone Value of 62, soundness loss of 1.8%, Los Angeles abrasion of 35%, and moisture content of 0.42%; Kandy aggregate returned corresponding values of 61, 1.9%, 30%, and 0.42%. These results satisfy the UK G1/S2 category thresholds for curves of radius below 500 m carrying up to 1,000 commercial vehicles per lane per day, confirming that domestic rock can technically replace imported calcined bauxite for this application [3,4].

The LCA results were, at first glance, counter-intuitive: although the epoxy resin used in HFST carries a far higher embodied-carbon factor (3.80 kg CO₂e/kg) than paving-grade bitumen (0.48 kg CO₂e/kg), the treatment's thin cross-section keeps total material use down to roughly 9.5 kg/m² versus over 100 kg/m² for an HMA overlay. HFST also avoids the plant-heating emissions inherent to hot-mix production. Across the 10-year horizon this yields a global warming potential of 5.85 kg CO₂e/m² for HFST, against 28.0 kg CO₂e/m² for DBST and 19.7 kg CO₂e/m² for HMA, a 39% reduction relative to the conventional overlay.

Table 1: Comparative material, environmental, and economic performance of the three resurfacing options over a 10-year horizon.

Parameter	HMA Overlay	DBST Emulsion	Polymer HFST
Friction service life (years)	4–6	2–4	>10
Re-treatment cycles, 10 yr	2	4	1
Material mass (kg/m ²)	100.8	44.0	9.45
Embodied carbon (kg CO ₂ e/m ²): a	19.7	28.0	5.85
Initial cost (US\$/m ²)	22.00	6.50	32.00
10-yr NPV, 4% discount (US\$/m ²)	40.08	19.10	32.00
Wet-weather crash reduction, assumed	20% (15–25%)	10% (5–25%)	50% (60–83%)
Benefit-cost ratio (BCR): b	0.56	0.58	1.74

a: Aggregate is assumed sourced from the Kandy quarry (≈ 35 km haul) and bitumen/emulsion/resin from Colombo (≈ 150 km).

b: Representative curve above; 6 crashes/yr (Sri Lankan black-spot threshold), 35% wet-weather share (rainfall-exposure proxy), and national casualty costs of US\$70,000/fatality (derived from published Sri Lankan human-capital estimates), US\$10,500/serious and US\$1,400/minor injury. Benefit-cost ratio (BCR) obtained by monetising the crash reduction attributable to each option at a representative highland curve (A5 Kandy–Nuwara Eliya corridor, radius <500 m; treated area 2,800 m², comprising a 150 m approach and 250 m curve body).

On a like-for-like initial-cost basis, HFST is the most expensive of the three. However, this comparison understates its practical case, because HFST is not proposed as a continuous-corridor resurfacing but as a spot treatment confined to the highest-risk curve approach and body. Applied only where crash risk is concentrated, its cost is incurred over a small treated area rather than the full carriageway length, while its friction service life exceeds ten years against four to six for HMA and two to four per DBST cycle, avoiding at least one, and possibly two, repeat interventions that a conventional treatment would require within the same period. Its reported wet-weather crash-reduction potential of 60–83%, roughly three to four times that of the alternatives, further strengthens the safety return per dollar spent when the treatment is targeted rather than applied uniformly [3,4].

Taken together, the material-testing and LCA/LCCA results indicate that on an empirical level, Anuradhapura- and Kandy-sourced aggregate can support a domestically manufactured HFST that is both lower-carbon and, when confined to genuinely high-risk curves, economically competitive with conventional resurfacing. Substituting local rock for imported calcined bauxite additionally removes the freight-related emissions and price volatility associated with overseas sourcing, positioning curve-specific HFST as a practical, sustainable safety intervention for Sri Lanka's central highland road network.

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SUSTAINABLE SPOT TREATMENT FOR SRI LANKA'S HIGHWAY CURVES

INTRODUCTION & PROBLEM

- ❖ Road Crash Statistics (Sri Lanka): ~38,000 crashes per year, resulting in over 3,000 fatalities and 8,000 serious injuries, causing an economic loss equal to 3–5% of national GDP.
- ❖ High-Risk Road Segments: Winding mountain alignments in the central highlands account for nearly 45% of fatal and grievous crashes due to excessive speed on hazardous horizontal curves.
- ❖ Supply Chain Bottleneck: High Friction Surface Treatment (HFST) adoption is hindered by the high cost of importing calcined bauxite and proprietary resins.

Proposed Solution:
Domestic aggregates
to develop an
affordable, low-
carbon HFST spot
treatment

METHODOLOGY & LIFE-CYCLE ASSESSMENT

- ❖ Aggregate Characterization: Geological samples from quarries were tested for PSV, LAHV, Soundness, and Moisture Content under UK and AASHTO HFST specifications.
- ❖ 10-Year Life-Cycle Modelling: A cradle-to-gate plus use-phase ISO 14040/14044 LCA and LCCA were conducted over a 1 m² functional unit across a 10-year service life.
- ❖ Evaluated Alternatives: 40-mm HMA overlay vs. DBST-2 cycles vs. Polymer-Resin HFST using local aggregate.
- ❖ Targeted Deployment Model: Spot treatment confined to high-friction demand zones rather than continuous corridor paving

RESULTS & KEY FINDINGS

- ❖ Local Aggregate Compliance: Anuradhapura (PSV 62, LAHV 35%) and Kandy (PSV 61, LAHV 30%) aggregates met UK G1/S2 specification thresholds, confirming local stone can replace imported calcined bauxite.
- ❖ 10-Year Carbon Footprint (GWP): HMA = 9.61 kgCO₂e/m²; DBST = 6.99 kgCO₂e/m²; HFST = 5.85 kgCO₂e/m² (achieving a 39% footprint reduction compared to HMA).
- ❖ Material Efficiency: HFST requires only 9.45 kg/m² total material mass compared to 100.8 kg/m² for an HMA overlay.
- ❖ Safety & Durability: Local HFST provides a friction service life exceeding 10 years and a wet-weather crash reduction potential of 60–83%

CLIMATE-INFORMED SPILLWAY DESIGN FOR HORUWILA WEWA UNDER FUTURE RAINFALL UNCERTAINTY

Md.R. Hassan^{1*}, C. Perera^{1,2}, N. Wijayaweera^{1,2}

¹ UNESCO Madanjeet Singh Centre for South Asia Water Management, University of Moratuwa, Moratuwa, Sri Lanka

² Department of Civil Engineering, University of Moratuwa, Moratuwa, Sri Lanka

**Corresponding author: mrh.md.rakibhassan@gmail.com*

Abstract

Intensity-Duration-Frequency (IDF) curves for water infrastructure are traditionally developed assuming climate stationarity. However, human-induced climate change has altered extreme rainfall patterns in recent decades, rendering historical curves untenable and raising global flood risk. Horuwila Wewa, an ancient reservoir in Anuradhapura with a catchment area of 26.4 km² within Sri Lanka's Dry Zone tank cascade system, faces growing challenges managing extreme rainfall under future climate change. This study aims to quantify climate projection uncertainty in future extreme rainfall and assess its implications for Horuwila Wewa's spillway design. Using observed rainfall (1995–2024) and downscaled projections from three Coupled Model Intercomparison Project Phase 6 (CMIP6) general circulation models (GCMs) (CNRM-CM6-1, HadGEM3-GC31-LL, MRI-ESM2-0) under shared socioeconomic pathways (SSPs) SSP2-4.5 and SSP5-8.5, 50-year return-period IDF curves were developed for 2041–2060 and 2081–2100. Daily extremes were estimated using the Gumbel distribution and disaggregated into sub-daily intensities using regional temporal distributions. The resulting IDF curves were incorporated into an uncalibrated HEC-HMS model to simulate reservoir inflows and determine the spillway length required to maintain target peak-pool stage under a 0.8 m bund-height increase. Peak inflow varied from **–13.1% to +57.8%** relative to the 283.8 m³/s baseline, reflecting substantial inter-model uncertainty. The most severe scenario (MRI-ESM2-0, SSP5-8.5, 2081–2100) required an **84% increase** in spillway length. The results demonstrate that climate projection uncertainty can substantially influence spillway design requirements. Incorporating multiple GCMs and SSPs into climate-informed IDF analysis can provide a more robust basis for adapting reservoir infrastructure to future extreme rainfall.

Keywords: Climate change, IDF curves, CMIP6, HEC-HMS, Spillway design

1. Introduction

Climate change is altering extreme rainfall events worldwide and raising flooding risk, which makes historically designed water infrastructure inadequate. Sri Lanka's North Central Dry Zone contains ancient tank cascade systems over two millennia old, whose bunds, sluices, and spillways were designed using historical rainfall data, an assumption that is increasingly untenable as extreme events intensify [1]. Consequently, infrastructure designed from historical IDF curves may be inadequate for current and future extreme events. This study aims to quantify uncertainty in future extreme rainfall projections from climate models and assess its implications for the spillway design of Horuwila Wewa. Figure 2 shows the study area.

2. Methodology

Limited research links climate-model uncertainty to IDF curves and spillway design in Sri Lanka's tank systems. This study addresses this gap by developing 50-year IDF curves using observed rainfall data from 1995–2024, three Coupled Model Intercomparison Project Phase 6

(CMIP6) general circulation models (GCMs), two SSPs, and two future periods, and assessing their implications at Horuwila Wewa using HEC-HMS. With a fixed 0.8 m bund enhancement, the study checks scenario-specific spillway requirements, providing a climate-informed basis for future water infrastructure design. Daily rainfall records from Anuradhapura station (1995–2024) were first checked and corrected for consistency and gaps. The Gumbel distribution was then fitted to the observed data to estimate the 50-year return period daily rainfall, which was disaggregated into sub-daily intensities using a region-specific temporal distribution [2]. An IDF curve for a 50-year return period was developed from this data, and the baseline 50-year design storm was estimated from the resulting curve. Coarse-resolution outputs from three GCMs (CNRM-CM6-1, HadGEM3-GC31-LL, and MRI-ESM2-0) were downscaled with Long Ashton Research Station-Weather Generator (LARS-WG) [3] for SSP2-4.5 and SSP5-8.5 across two future periods (2041–2060 and 2081–2100). Repeating the baseline procedure, future IDF curves and 50-year design storms were estimated for all twelve future scenarios. The 50-year return period was held fixed across all scenarios, as it is consistent with established Sri Lankan practice [2], so that the resulting variation in spillway length reflects climate-model and scenario uncertainty rather than differences in design standard. All 13 design storms (baseline plus projections) were routed through an identical uncalibrated HEC-HMS model of Horuwila Wewa, developed using the SCS method for transformation and unit hydrograph generation. A 0.8 m bund augmentation, required for the baseline, was kept constant across all 12 future scenarios. Spillway length was varied for each scenario until the target peak was achieved, making the required spillway length a direct measure of climate-driven infrastructure adaptation needs. Due to the lack of observed streamflow data, the HEC-HMS models could not be calibrated; therefore, the simulated peak inflows remain subject to uncertainty.

3. Results and Discussion

Figure 1 compares the baseline (1995–2024) IDF curve with SSP2-4.5 and SSP5-8.5 projections for two future periods. Baseline intensity starts near 1,100 mm/h at 5 minutes, dropping below 50 mm/h after 3 hours. Since the same regional temporal distributions derived from existing IDF curves were used to disaggregate daily rainfall for all scenarios, the projected percentage change in rainfall intensity is similar across durations. However, the absolute change is much larger for shorter durations because their baseline intensities are substantially higher.

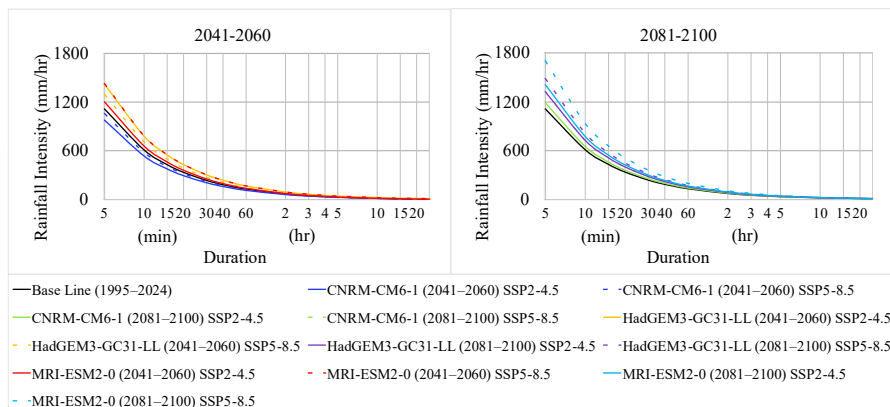


Figure 1: Comparison of baseline and future projections (three CMIP6 GCMs, two SSPs, and two future periods) IDF curves.

For instance, MRI-ESM2-0 SSP5-8.5 (2081–2100) shows a ~53% increase at both the 5-minute and 1-hour durations, but because baseline intensity is far higher at 5 minutes, the resulting absolute increase is much larger there (591.45 mm/h vs. 69.28 mm/h). The IDF curves show divergence peaks at short durations (5–30 min), especially under SSP5-8.5/2081–2100, indicating that short-duration extremes are among the factors affecting spillway and inflow requirements. Table 1 summarises the peak reservoir inflow and required spillway length for all thirteen scenarios.

Table 1: Baseline and projected 50-year return-period peak reservoir inflow and required spillway length to maintain the target peak-pool elevation under 13 HEC-HMS simulations.

Model	SSP	Period	Peak Inflow (m ³ /s)	Δ Peak Inflow (%)	Spillway (m)	Δ Spillway (%)
Baseline	—	1995–2024	283.8	—	25	—
CNRM-CM6-1	SSP2-4.5	2041–2060	246.6	–13.1	20	–20.0
		2081–2100	304.3	+7.2	28	+12.0
	SSP5-8.5	2041–2060	269.0	–5.2	23	–8.0
		2081–2100	342.0	+20.5	33	+32.0
HadGEM3-GC31-LL	SSP2-4.5	2041–2060	368.8	+30.0	36	+44.0
		2081–2100	341.9	+20.5	33	+32.0
	SSP5-8.5	2041–2060	333.8	+17.6	32	+28.0
		2081–2100	387.9	+36.7	38	+52.0
MRI-ESM2-0	SSP2-4.5	2041–2060	308.0	+8.5	29	+16.0
		2081–2100	367.0	+29.3	36	+44.0
	SSP5-8.5	2041–2060	371.1	+30.8	36	+44.0
		2081–2100	447.7	+57.8	46	+84.0

Ten of twelve scenarios project inflow increases above the 283.8 m³/s baseline; only CNRM-CM6-1 (2041–2060) shows decreases (–13.1% SSP2-4.5, –5.2% SSP5-8.5). MRI-ESM2-0 yields the largest increases, and CNRM-CM6-1 the lowest. The most extreme scenario (MRI-ESM2-0/SSP5-8.5/2081–2100) shows a 57.8% inflow increase, requiring an 84% longer spillway. Required spillway lengths range from 20 to 46 m. Climate change intensifies short-duration rainfall extremes, driving inflow and spillway needs up to 84% above baseline, underscoring the need for climate-informed IDF curves in water infrastructure planning.

Acknowledgements

The authors gratefully acknowledge the UNESCO Madanjeet Singh Centre for South Asia Water Management and South Asia Foundation for their continued support throughout this study.

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CLIMATE-INFORMED SPILLWAY DESIGN FOR HORUWILA WEWA UNDER FUTURE RAINFALL UNCERTAINTY

Significance & Aim

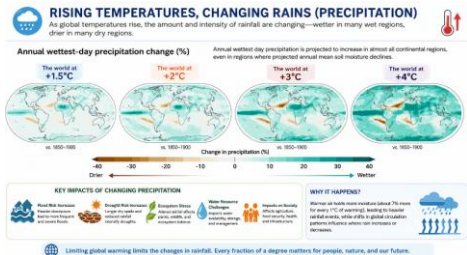
Significance

- Intensity-Duration-Frequency (IDF) curves for water infrastructure have traditionally been developed under the assumption of climate stationarity.
- Human-induced climate change has altered extreme rainfall patterns over the past few decades, rendering historical IDF curves increasingly unreliable.
- Water infrastructure designed using historical IDF curves may be inadequate for future extreme events.

Aim

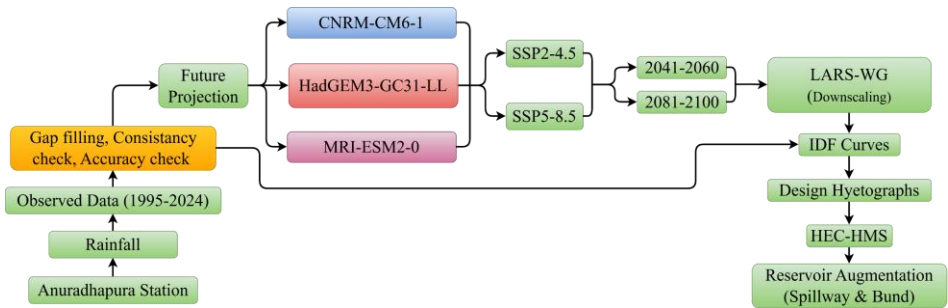
To develop climate-informed IDF curves for designing future water management infrastructure and their implementations.

Significance



Source: ChatGPT (OpenAI)

Methodology



Study Area, Results & Discussion

Study Area

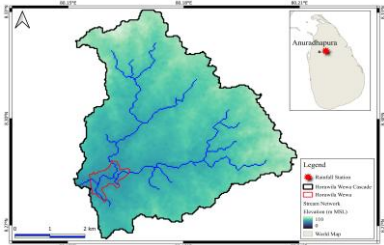
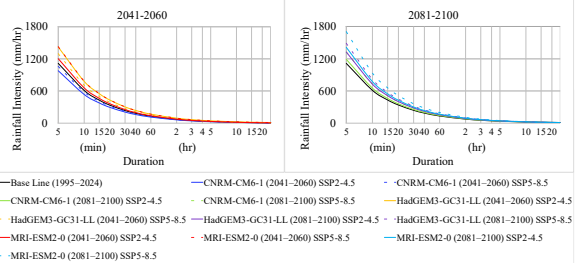


Figure 2: Horuwila Wewa Cascade.

Results



Discussion

- Short-duration rainfall extremes intensify disproportionately, with the greatest IDF changes at 5–30 minutes, increasing peak inflow risks.
- Most scenarios increase peak inflow and spillway requirements, with the extreme scenario showing a **57.8%** inflow increase and requiring an **84%** longer spillway.

Model	SSP	Period	Peak Inflow (m³/s)	ΔPeak Inflow (%)	Spillway (m)	ΔSpillway (%)
Baseline	—	1995–2024	283.8	—	25	—
		2041–2060	246.6	−13.1	20	−20.0
		2081–2100	304.3	+7.2	28	+12.0
CNRM-CM6-1	SSP2-4.5	2041–2060	269.0	−5.2	23	−8.0
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		2081–2100	367.0	+29.3	36	+44.0
		2041–2060	371.1	+30.8	36	+44.0
		2081–2100	447.7	+57.8	46	+84.0

QUANTIFYING RESERVOIR CAPACITY ENHANCEMENT AND SPILLWAY DESIGN UNDER FUTURE CLIMATE SCENARIOS IN THE KATTIYAWA WEWA, KNUCKLES BASIN, SRI LANKA

R.L.H.L. Rajapakse¹, H. Ratnasooriya¹, S. Akhter^{1*}

¹ UMCSAWM, Department of Civil Engineering, University of Moratuwa, Sri Lanka

**Corresponding author: shahrinakhter28@gmail.com*

Abstract

This study assessed future climate impacts on Sri Lanka's Kattiyawa Wewa Reservoir, located downstream of the Knuckles Basin. It quantified the reservoir capacity augmentation and spillway design upgrades required under those scenarios. Future daily precipitation projections from three Coupled Model Intercomparison Project Phase 6 (CMIP6) global climate models (GCMs) (CNRM-CM6-1, HadGEM-GC31-LL, and MRI-ESM2-0) under SSP2-4.5 and SSP5-8.5 scenarios were statistically downscaled to the watershed level for the 2041–2060 and 2081–2100 periods using LARS-WG software. The downscaled daily data were disaggregated to sub-daily durations using to develop Intensity-Duration-Frequency curves. These rainfall inputs were incorporated into the HEC-HMS hydrological model, configured with SCS Curve Number loss method and unit hydrograph transforms, to simulate design flood hydrographs and estimate critical peak discharges for various return periods. Results show peak discharges rising drastically, up to 1,378 m³/s under the HadGEM-GC31-LL SSP5-8.5 scenario by 2081–2100, representing a 215% increase from baseline conditions. Using area–capacity curves derived from the non-dimensional relationship developed for small tanks in Sri Lanka, required storage enhancement ranges from 55% to over 200%, depending on the climatic scenario. Spillway capacity must be upgraded to 1,100–1,200 m³/s with concurrent storage expansion, or up to 1,380 m³/s without it. Existing infrastructure is shown to be inadequate under most scenarios. Adaptive strategies include reservoir capacity enhancement, combined with operational flexibility to manage variable inflows, preventing overtopping, reducing downstream flooding, and ensuring long-term dam safety.

Keywords: Climate change, Downscaling, HEC-HMS, SSP scenarios

1. Introduction

Climate change introduces substantial uncertainty into hydrological design by altering extreme precipitation and streamflow patterns [1]. Global warming has intensified the hydrological cycle and increased the occurrence of extreme flood events, challenging the stationarity assumption underlying conventional reservoir design based on historical records [1,2]. The Knuckles Basin is a crucial watershed in central Sri Lanka, supporting over 1.3 million people through agriculture, hydropower, and water supply. Although it harbours rich biodiversity, it is highly vulnerable to climate-induced hydrological extremes. Particularly, intensification of extreme events challenges the stationarity assumption in conventional reservoir design, leaving much existing infrastructure vulnerable to future conditions. Recent literature highlights increasing hydrological variability and growing flood risks under global warming [1], while regional studies emphasise Sri Lanka's susceptibility to changing inflows and the need for adaptive infrastructure [3]. However, quantitative Coupled Model Intercomparison Project Phase 6 (CMIP6)-based vulnerability assessments remain scarce for the Knuckles Basin. Therefore, this study aims to assess the adequacy of the existing Kattiyawa Wewa Reservoir

and identify the required modifications to its storage capacity and spillway system under future climate conditions.

2. Methodology

This study focuses on the Kattiyawa Wewa Reservoir within Sri Lanka's Knuckles Basin, covering an area of 114.57 km². Historical observed rainfall data were collected from local meteorological authorities, while future climate projections were downscaled from three CMIP6 GCMs (CNRM-CM6-1, HadGEM-GC31-LL, and MRI-ESM2-0) under SSP2-4.5 and SSP5-8.5 scenarios for the 2041–2060 and 2081–2100 periods using the LARS-WG statistical downscaling tool [4]. The resulting daily rainfall series were then used to develop future Intensity-Duration-Frequency (IDF) curves, with daily rainfall values disaggregated using regionally developed by Engr. Ponrajah. The projected rainfall scenarios were then incorporated into the HEC-HMS hydrological model to simulate design flood hydrographs and estimate critical peak discharges. However, during data analysis the model was not calibrated. Concurrently, DEM data were used to develop the reservoir area–capacity curve based on the non-dimensional relationship developed for small village tanks in Sri Lanka [4]. This approach requires only a limited number of key measurements, enabling rapid estimation of reservoir storage characteristics without the need for extensive field surveys. The estimated peak discharges and required storage augmentation were then integrated to guide spillway design, ensuring the reservoir can safely accommodate future flood conditions. Finally, all findings were synthesised to formulate recommendations for climate-resilient reservoir management and necessary infrastructure upgrades.

3. Results and Discussion

Figure 1 shows the systematic analysis of future flood dynamics through an integrated hydrological and reservoir modelling framework. The design hydrograph illustrates projected discharge variations over time. The peak discharge indicates that the HadGEM-GC31-LL model projects the most extreme values, reaching 1378.1 m³/s under both SSP2-4.5 and SSP5-8.5 scenarios for the 2081–2100 period, more than three times the baseline peak discharge of 437.2 m³/s for 1994–2024. In contrast, the CNRM-CM6 model yields moderate projections (679.8–751.2 m³/s). The CNRM-CM6 and the MRI-ESM2-0 under SSP5-8.5, 2081–2100 had identical peak discharge. This inter-model variability emphasises the inherent uncertainty in climate projections and highlights the critical role of GCM selection in flood risk assessment.

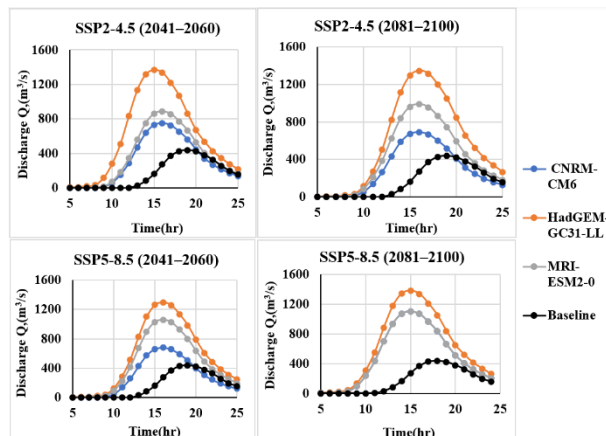


Figure 1: Design hydrograph.

Table 1 presents the projected peak discharge values (in m³/s) for the Kattiyawa Wewa reservoir under three different GCMs and two emission scenarios and future time periods.

Table 1: Peak discharge projections under future climate scenarios.

Peak Discharge (m³/s)					
CNRM-CM6, SSP2-4.5	2041–2060	751.2	HadGEM-GC31-LL, SSP5-8.5	2041–2060	1297.6
	2081–2100	691.8		2081–2100	1378.1
CNRM-CM6, SSP5-8.5	2041–2060	679.8	MRI-ESM2-0, SSP2-4.5	2041–2060	887.3
	2081–2100	1102.4		2081–2100	988.9
HadGEM-GC31-LL, SSP2-4.5	2041–2060	1370.5	MRI-ESM2-0, SSP5-8.5	2041–2060	1059.9
	2081–2100	1346.2		2081–2100	1102.1

Sometimes, under different climate scenarios and parameters, the peak discharge can be similar. The HadGEM-GC31-LL model consistently produces the most extreme flows, exceeding baseline levels (437.2 m³/s) by over 215%, underscoring the urgency for reservoir capacity and spillway upgrades.

These findings reveal extreme flood vulnerability in the coming decades, with impacts strongly dependent on GCM and emissions trajectory. The integrated design hydrograph and reservoir routing framework underscores the critical need to augment the reservoir capacity and increase spillway length to tackle future extreme climatic events.

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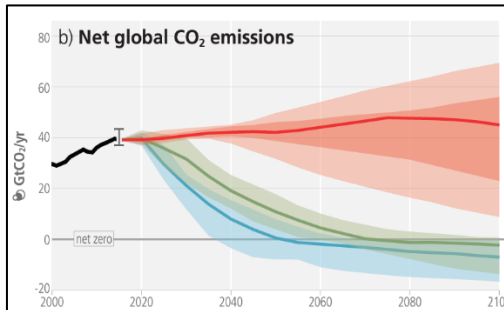
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QUANTIFYING RESERVOIR CAPACITY ENHANCEMENT AND SPILLWAY DESIGN UNDER FUTURE CLIMATE SCENARIOS IN THE KATTIYAWA WEDA, KNUCKLES BASIN, SRI LANKA

Background

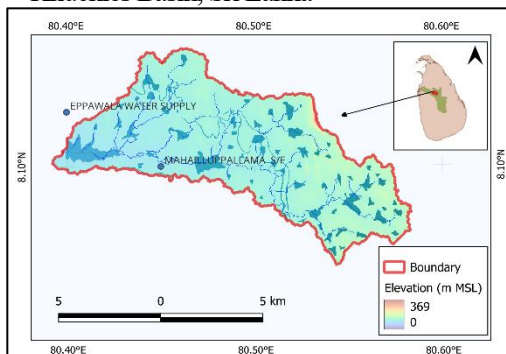


- The frequency and intensity of heavy precipitation events have increased since the 1950s.
- Annual wettest-day precipitation is projected to increase in almost all continental regions, even in areas where mean soil moisture is projected to decline.

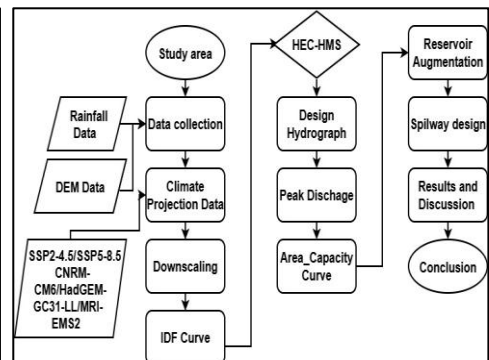
Source: IPCC AR6 Figure SPM.5: Global emissions pathways

Research Methodology

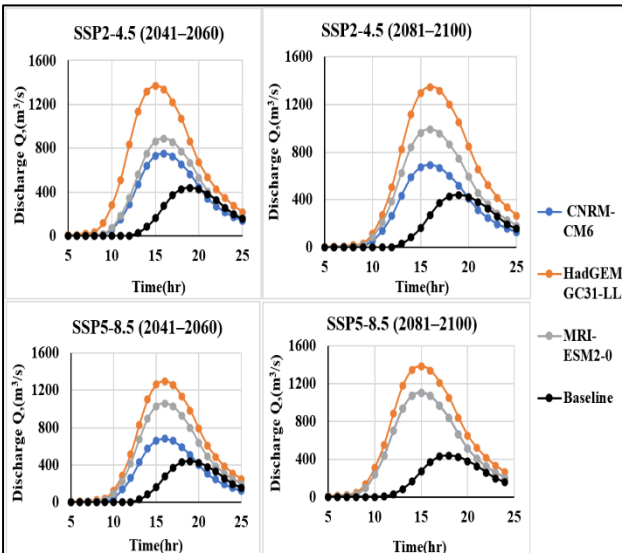
Study area: The Kattiyawa Wewa, Knuckles Basin, Sri Lanka



Research Methodological Flowchart



Results and Conclusion



- Peak discharges are projected to rise by up to 215% above the baseline.
- Reservoir storage capacity must be increased by 55% to over 200%
- Spillway discharge capacity must be upgraded to at least 1,100–1,200 m³/s.

ASSESSING THE INFLUENCE OF RAINFALL-INTENSITY-DEPENDENT TIME OF CONCENTRATION ON SPILLWAY DESIGN UNDER FUTURE CLIMATE SCENARIOS IN THE KNUCKLES BASIN, SRI LANKA

R.L.H.L. Rajapakse¹, N.K. Gunasekara², S.T. Zaman^{1*}

¹ UNESCO Madanjeet Singh Centre for South Asia Water Management, University of Moratuwa, Moratuwa, Sri Lanka

² Department of Civil Engineering, KDU, Ratmalana, Sri Lanka

**Corresponding author: syedtakrimzaman@gmail.com*

Abstract

Although conventional hydrological design treats time of concentration (T_c) as a static constant, T_c is inversely related to rainfall intensity, making its dynamic representation important under climate change. This study assesses how rainfall-intensity-dependent T_c affects spillway design under future climate scenarios in the Knuckles Basin, Sri Lanka. Future climate projections were obtained from three CMIP6 GCMs (CNRM-CM6-1, HadGEM3-GC31-LL, MRI-ESM2-0) under SSP2-4.5 and SSP5-8.5, statistically downscaled to watershed level for 2041–2060 and 2081–2100 using LARS-WG. The resulting daily rainfall series were then used to develop future Intensity-Duration-Frequency (IDF) curves, with daily rainfall values disaggregated using a regionally developed by Engr. Ponrajah. An existing rainfall intensity- T_c relationship, developed using Detrended Moving-Average Cross-Correlation Analysis (DMCA), was adopted to estimate rainfall-intensity-dependent T_c , and hydrological simulations were performed in HEC-HMS using the SCS Unit Hydrograph method. The dynamic T_c relationship was incorporated into design-storm simulations to evaluate hydrograph shape, peak discharge, and spillway response. Results demonstrate an inverse relationship between rainfall intensity and T_c , with T_c decreasing from approximately 2.5 to 1.0 hours as intensity increases from 25 to 45 mm/h. Projected peak discharge varied substantially across climate projections, ranging from 81.6 to 205.4 m³/s. MRI-ESM2-0 under SSP5-8.5 for 2081–2100 produced the highest projected peak, reaching 205.4 m³/s, approximately 2.5 times the baseline peak discharge of 82.2 m³/s. To convey this maximum inflow, the spillway design required an increase in crest length from 58 m to 80 m and crest elevation from 72 m to 73 m, which attenuated the reservoir peak discharge from a baseline of 525 m³/s to 179.6 m³/s. These findings highlight the importance of dynamic T_c and multi-model climate projections for climate-resilient spillway design.

Keywords: Climate change, Hydrological modelling, Flood risk, Time of concentration, Spillway design

1. Introduction

Time of concentration (T_c) is the time required for water from the hydraulically most distant point of a catchment to reach the catchment outlet after the start of rainfall. Research has demonstrated that increasing rainfall intensity shortens catchment response time, producing sharper and higher flood peaks than conventional fixed- T_c approaches would predict [1,2]. However, the implications of this dynamic response for spillway design under future climate scenarios remain inadequately explored, particularly in data-scarce tropical watersheds. This study aims to assess the influence of rainfall-intensity-dependent T_c on spillway design in the Knuckles Basin, with the specific objective of evaluating how this dynamic relationship affects

design hydrograph peaks and consequently the required spillway crest length, elevation, and discharge efficiency under climate projections.

2. Methodology

The Pahala Halmillewa Wewa, situated at the Knuckles Basin, was selected as the study area owing to its critical role as a water source and its recognised vulnerability to climate-induced extreme events. Daily precipitation data for 30 years, from 1995 to 2024, were obtained from the Anuradhapura gauging stations following World Meteorological Organization (WMO) guidelines, while future climate projections were derived from three GCMs, CNRM-CM6-1, HadGEM3-GC31-LL, and MRI-ESM2-0, under the SSP2-4.5 and SSP5-8.5 scenarios for the 2041–2060 and 2081–2100 periods using the LARS-WG statistical downscaling tool [3]. The resulting daily rainfall series were then used to develop future Intensity-Duration-Frequency (IDF) curves, with daily rainfall values disaggregated using regionally developed by Engr. Ponrajah. Hydrological modelling was performed using HEC-HMS with the SCS Unit Hydrograph Method. The relationship between rainfall intensity and T_c was established using the Detrended Moving-Average Cross-Correlation Analysis (DMCA) approach established in the literature [1]. The resulting hydrographs were evaluated in terms of peak discharge, time to peak, and overall hydrograph response to identify the influence of varying T_c on flood magnitude and catchment response. Reservoir routing was then used to assess the attenuation of peak inflows and the resulting outflow response. The analysis further considered the implications of the projected flood peaks for spillway design, particularly in relation to spillway crest elevation, crest length, and discharge efficiency under future climate conditions.

3. Results and Discussion

The design hydrographs demonstrate substantial inter-model variability in peak discharge and catchment response under future climate scenarios. The highest plotted peak, approximately $205 \text{ m}^3/\text{s}$, is produced by MRI-ESM2-0, exceeding the baseline peak by approximately 150%, indicating considerable uncertainty in projected flood magnitude.

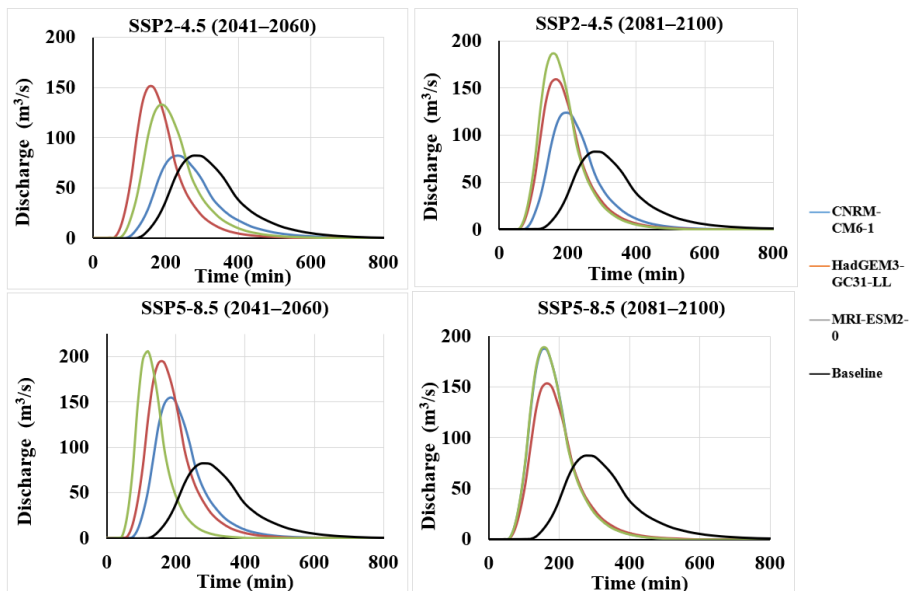


Figure 1: Design hydrograph.

Under baseline conditions, the spillway crest length was 58 m, the crest elevation was 72 m, and the reservoir peak discharge was 525 m³/s. To manage a maximum peak inflow of 205.4 m³/s, the design was revised to a crest length of 80 m and crest elevation of 73 m, which successfully attenuated the peak discharge at the reservoir to 179.6 m³/s.

The Tc vs. rainfall intensity analysis reveals a strong inverse linear relationship between rainfall intensity and time of concentration (Tc), where Tc decreases from approximately 2.5 hours to 1.0 hour as intensity increases from 25 mm/h to 45 mm/h. This finding challenges the conventional static Tc assumption and aligns with the HEC-HMS application-guide example demonstrating that reducing Tc produces a unit-hydrograph peak approximately 50% higher than the original estimate.

Table 1 indicates that the maximum projected peak discharge occurs under the MRI-ESM2-0 model for SSP5-8.5 during 2081–2100, representing approximately 2.5 times the baseline peak discharge (82.2 m³/s).

Table 1: Peak discharge projections under future climate scenarios.

Projection Model	Duration	Peak Discharge(m ³ /s)	Projection Model	Duration	Peak Discharge(m ³ /s)
CNRM-CM6-1, SSP 2-4.5	2041–2060	81.6	HadGEM3-GC31-LL, SSP 5-8.5	2041–2060	153.8
	2081–2100	124.1		2081–2100	193.7
CNRM-CM6-1, SSP 5-8.5,	2041–2060	186.8	MRI-ESM2-0, SSP 2-4.5	2041–2060	132.2
	2081–2100	154.3		2081–2100	185.6
HadGEM3-GC31-LL, SSP 2-4.5	2041–2060	150.2	MRI-ESM2-0, SSP 5-8.5	2041–2060	188.1
	2081–2100	159.6		2081–2100	205.4

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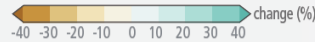
[2] Calvin K, Dasgupta D, Krinner G *et al.* *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (Eds.)]. IPCC, Geneva, Switzerland, ed. Arias P, Bustamante M, Elgizouli I et al. 2023.* <https://doi.org/10.59327/IPCC/AR6-9789291691647>.

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ASSESSING THE INFLUENCE OF RAINFALL-INTENSITY-DEPENDENT TIME OF CONCENTRATION ON SPILLWAY DESIGN UNDER FUTURE CLIMATE SCENARIOS IN THE KNUCKLES BASIN, SRI LANKA

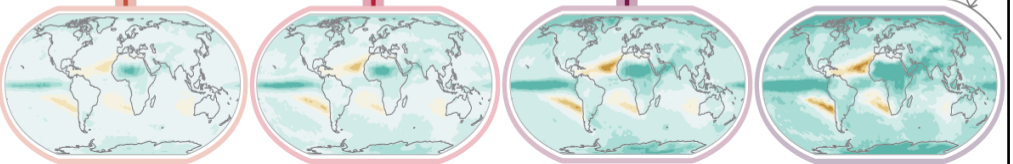
Background

c) Annual wettest-day precipitation change



Annual wettest day precipitation is projected to increase in almost all continental regions, even in regions where projected annual mean soil moisture declines.

small absolute changes may appear large as % or σ changes in dry regions

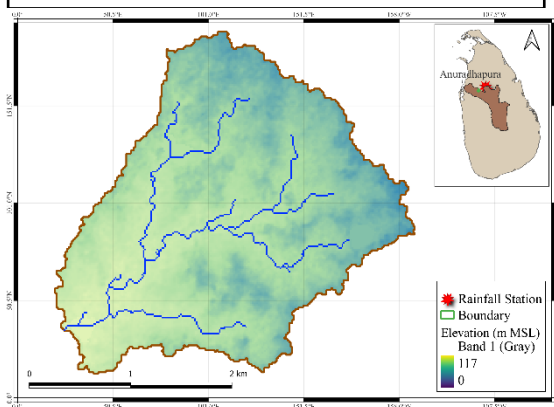


The projected increase in frequency and intensity of heavy precipitation (high confidence) will increase rain-generated local flooding (medium confidence). [2]

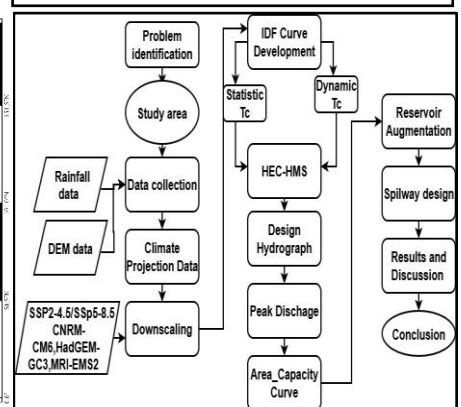
Source: IPCC (2023), AR6 Synthesis Report, Figure SPM.2.

Research Methodology

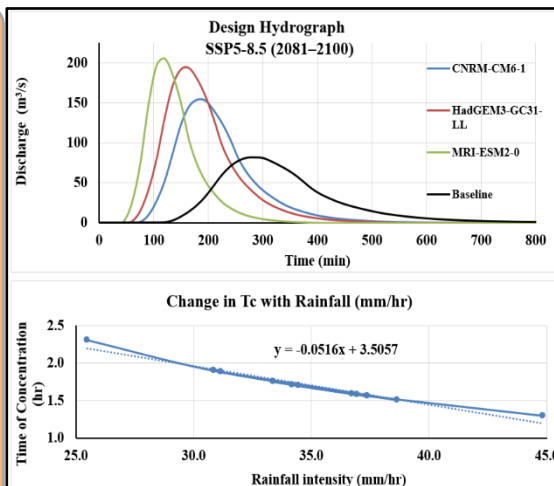
Study area: Pahala Halmillewa Wewa, Knuckles Basin, Sri Lanka



Methodological flowchart



Results and Conclusion



- Rainfall intensity and T_c showed a strong inverse relationship, decreasing from ~2.5 h to 1.0 h as intensity increased from 25–45 mm/h.
- **Spillway design summary:**
 - I. Required crest length increase: 58 m to 80 m
 - I. Required crest elevation increase: 72 m to 73 m
 - I. Reservoir peak discharge reduction: 525 m³/s to 179.6 m³/s

EVALUATING THE PERFORMANCE OF GNSS RTK AND UAV (DRONE) TECHNOLOGIES UNDER VRS MODE IN CHALLENGING ENVIRONMENTS

Sudhara Gallage^{1*}, Chamod Hettiarachchi¹

¹ Department of Civil Engineering, University of Moratuwa, Moratuwa, Sri Lanka

**Corresponding author: sudharagallage@gmail.com*

Abstract

Reliable geospatial data acquisition in obstructed environments is important for engineering surveying, but buildings, vegetation, multipath, and operational restrictions can reduce positioning reliability. This field study compared Global Navigation Satellite System Real-Time Kinematic (GNSS RTK), an RTK-enabled unmanned aerial vehicle (UAV) using Virtual Reference Station (VRS) corrections, and handheld Simultaneous Localisation and Mapping (SLAM) across urban, forested, mixed-use, and semi-urban sites in Sri Lanka. Static GNSS and closed Total Station traverses established the reference coordinates. GNSS RTK was tested at all four sites, UAV RTK only in the urban corridor, and SLAM in the forested and mixed-use sites. Horizontal performance was assessed using root mean square error (RMSE), median, 95th percentile, maximum error, and availability. GNSS RTK RMSE values ranged from 0.064 to 0.121 m, UAV RTK recorded 0.106 m in the urban corridor, and SLAM recorded 0.160 m in the forest and 0.299 m in the mixed-use site. GNSS RTK gave the lowest errors where a stable FIX was available; UAV RTK provided rapid coverage, while SLAM maintained continuous mapping with higher drift-related error. Technology selection should therefore reflect required accuracy, coverage, access, and operating constraints.

Keywords: Surveying, LiDAR mapping, SLAM, Positional accuracy, Infrastructure monitoring

1. Introduction

GNSS RTK can provide centimetre-level positioning in favourable conditions, while RTK-enabled UAVs and LiDAR-based mobile mapping support rapid spatial data acquisition. Urban canyons, dense vegetation, and terrain masking reduce satellite visibility and introduce multipath and non-line-of-sight signals [1]. Network RTK and VRS reduce distance-dependent atmospheric errors but cannot remove local obstruction effects [2].

Previous studies commonly evaluate GNSS RTK, UAV mapping, or alternative positioning methods separately [3,4]. This study provides a field-based comparison of current GNSS RTK, UAV LiDAR, and handheld SLAM applications in engineering surveying using a common reference framework. The objectives were to compare horizontal accuracy and availability, examine environmental effects, and provide task-specific technology-selection guidance.

2. Materials and Methods

Four environments were studied: the Sarasavi Mawatha urban corridor at the University of Kelaniya, Kaju Kale forest and a mixed-use campus area at the University of Moratuwa, and a semi-urban preliminary site at Pita Kotte.

Reference coordinates were established from approximately one-hour static GNSS observations and post-processed closed Total Station traverses. All traverse networks satisfied a closing linear fractional error of 1/10,000 or better. Point-level covariance for the adjusted reference coordinates was not retained, so formal uncertainty propagation was not possible;

reported errors are therefore discrepancies relative to the adjusted reference network. GNSS RTK was collected at all four sites; DJI Matrice 350 RTK/Zenmuse L2 data were collected only in the urban corridor; and a GoSLAM M40 was used in the forested and mixed-use sites because UAV approval was unavailable near Ratmalana Airport. The semi-urban site used GNSS RTK only.

UAV and SLAM point clouds were processed in 3Dsurvey and compared with reference checkpoints. Easting and Northing differences were used to calculate horizontal error, RMSE, median, 95th percentile, maximum error, and availability. N denotes common checkpoints used in each statistical comparison; availability denotes usable observations relative to planned checkpoints.

3. Results and Discussion

Table 1 reports the requested sample size, error-distribution statistics, and field availability for each dataset.

Table 1: Comparative horizontal positioning performance.

Site	Tech.	N	Median (m)	RMSE (m)	95th pct. (m)	Max (m)	Avail. (%)
Urban	GNSS RTK	15	0.044	0.064	0.110	0.115	100
Urban	UAV RTK	15	0.091	0.106	0.170	0.252	83.3
Forest	GNSS RTK	16	0.075	0.079	0.103	0.107	84.3
Forest	SLAM	16	0.139	0.160	0.257	0.358	100
Mixed-use	GNSS RTK	19	0.068	0.074	0.099	0.113	100
Mixed-use	SLAM	19	0.287	0.299	0.486	0.489	100
Semi-urban	GNSS RTK	35	0.106	0.121	0.186	0.216	100

GNSS RTK showed lower central and tail errors than UAV RTK in the urban corridor, while UAV availability fell to 83.3% because three of 18 planned points were unavailable. Forest GNSS RTK retained lower errors at valid FIX stations but availability fell to 84.3%; SLAM maintained full route coverage with higher error. Mixed-use SLAM showed the largest tail error (95th percentile 0.486 m; maximum 0.489 m). Figure 1 shows the median, 95th percentile, and maximum error for each dataset rather than repeating the RMSE-only comparison.

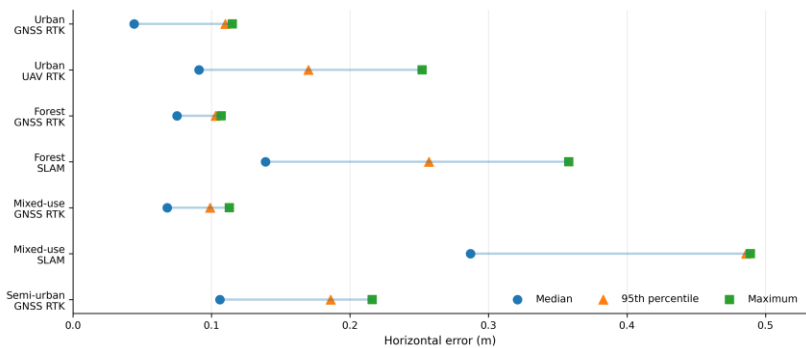


Figure 1: Horizontal error distribution summary by technology and environment.

4. Practical Implications

GNSS RTK is appropriate for accuracy-critical control where a stable FIX is available. UAV RTK can support rapid corridor or area mapping when its approximately 0.1 m RMSE and flight conditions meet project tolerances. SLAM preserved continuity in the forested and mixed-use sites, but its 0.160-0.299 m RMSE limits use for precision control; UAV and SLAM outputs should be verified against independent GNSS or Total Station control for engineering decisions.

5. Conclusions

GNSS RTK produced the lowest horizontal errors but lost availability beneath dense canopy. UAV RTK provided rapid urban coverage but showed greater variability and missing observations under severe obstruction. SLAM maintained continuous coverage where UAV operation was not feasible, although drift reduced accuracy. Technology should therefore be selected by task and tolerance rather than treated as interchangeable. Future work should retain reference-network covariance for formal uncertainty propagation and examine mountainous terrain and tighter GNSS-inertial-LiDAR-SLAM integration.

Acknowledgements

The authors gratefully acknowledge the Department of Civil Engineering, University of Moratuwa, for academic and institutional support. Special appreciation is extended to GLOBAL GIS (PVT) LTD for providing GNSS RTK, UAV LiDAR and SLAM equipment, data-processing facilities, technical guidance, and field support. The authors also acknowledge SULECO (PVT) LTD for facilitating the preliminary semi-urban field investigation.

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Evaluating the Performance of GNSS RTK and UAV (Drone) Technologies
under VRS Mode in Challenging Environments

Graphical Abstract

1 Study environments and technology coverage



Environmental complexity affects both positioning accuracy and operational feasibility.

2 Reference framework and workflow



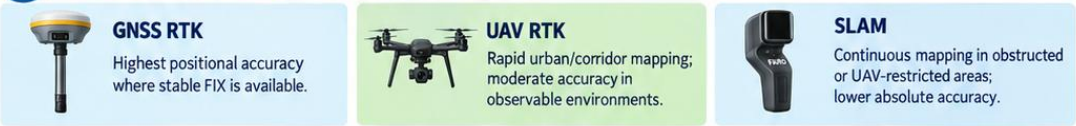
UAV approval unavailable at University of Moratuwa sites near Ratmalana Airport.

3 Key quantitative results

Environment	Technology	RMSE (m)	Availability (%)	RMSE (m) – visual	Availability (%) – visual
Urban	GNSS RTK	0.064	100	0.064	100
	UAV RTK	0.106	83.3	0.106	83.3
Forest	GNSS RTK	0.079	84.3	0.079	84.3
	SLAM	0.160	100	0.160	100
Mixed-use	GNSS RTK	0.074	100	0.074	100
	SLAM	0.299	100	0.299	100
Semi-urban	GNSS RTK	0.121	100	0.121	100

Forest GNSS RTK values are based on valid FIX observations. Lower RMSE indicates higher accuracy.

4 Main findings and practical guidance



No single technology is optimal in every setting. Select the method according to required accuracy, spatial coverage, site access, and operating constraints.

EXPERIMENTAL AND NUMERICAL INVESTIGATION OF DOWEL BAR MISALIGNMENT IN THIN RIGID PAVEMENT JOINTS

D.P.H.D. Ubeseekara^{1*}, W.R.A.N. Jayantha¹, R.M.C.M. Rajapakse¹

¹ Department of Civil Engineering, University of Moratuwa

**Corresponding author: ubeseekarahasini@gmail.com*

Abstract

Dowel bars transfer loads across transverse joints in jointed plain concrete pavements while allowing joint movement. Angular misalignment can increase restraint and local stresses at the dowel-concrete interface. Previous studies have mainly focused on thicker highway and airport pavements with relatively large dowels, while thin rigid pavements with smaller dowels remain less studied. This study experimentally and numerically investigates dowel misalignment in 150 mm thick concrete slab pairs connected by a 20 mm diameter steel dowel. Six specimens representing aligned, horizontal, vertical, and combined misalignment conditions were tested under progressive horizontal displacement. A three-dimensional nonlinear finite element model incorporating Concrete Damaged Plasticity (CDP) and dowel-concrete contact was developed. Misalignment generally increased pull-out resistance and local stress concentration; the 6.3° vertical case produced the highest experimental resistance of 7.5 kN and the most pronounced tensile damage. Excluding the compromised H3.1 test, the model reproduced the aligned and single-plane peak loads within 4.0-15.6%. The findings indicate that vertical misalignment requires particular construction control because increased joint restraint and localised damage may contribute to premature joint deterioration.

Keywords: Jointed plain concrete pavements, Nonlinear finite element modelling, Stress distribution, Pull-out resistance

1. Introduction

Dowel bars transfer load across transverse joints while permitting movement caused by temperature and shrinkage. Misalignment during construction can restrict this movement, increase restraint at the dowel-concrete interface, and contribute to cracking, spalling, and joint deterioration [1-5]. Recent numerical studies have also demonstrated the value of nonlinear finite element modelling for evaluating dowel response, stress redistribution, and concrete damage. Most previous studies have considered conventional highway and airport pavements with thicker slabs and larger dowels. The behaviour of thin rigid pavements using smaller dowels, relevant to low-volume roads, remains less understood, particularly the influence of misalignment orientation on restraint and local damage.

This study therefore evaluates the pull-out response, stress development, and concrete damage associated with aligned, horizontal, vertical, and combined dowel misalignment using experimental testing and three-dimensional nonlinear finite element analysis.

2. Methodology

Six paired concrete-block specimens were prepared using 150 mm thick Grade 30 concrete slabs separated by a 3 mm joint. Each specimen contained a 20 mm diameter, 400 mm long steel dowel. The programme comprised an aligned control, horizontal and vertical

misalignments of 3.1° and 6.3° , and a combined case with approximately 3.1° horizontal and 3.1° vertical misalignment. One specimen was tested per configuration; therefore, the programme was intended to identify comparative behavioural trends rather than quantify specimen-to-specimen variability.

Horizontal displacement was progressively applied using a jack, with load measured by load cells and displacement by LVDTs. Roller supports and lateral restraints maintained the intended configuration. Load-displacement response and visible cracking, crushing, and spalling around the dowel-concrete interface were recorded.

A three-dimensional nonlinear finite element model reproduced the specimen geometry, loading, and restraint conditions. Concrete was represented using CDP calibrated for Grade 30 concrete, while the steel dowel was modelled as elastic-plastic. Hard normal contact and penalty friction were used at the interface, with coefficients of 0.05 on the greased side and 0.30 on the bonded side. The mesh was locally refined around the dowel-concrete interface, where high stress gradients were expected. Displacement-controlled nonlinear static analysis with automatic incrementation was adopted for convergence. Experimental load-displacement response and observed distress were used to assess the model. A formal mesh-sensitivity study was not included in the present experimental-stage analysis and is recognised as a numerical limitation.

3. Results and Discussion

The experimental results in Table 1 show that misalignment substantially influenced joint restraint. Greater angular misalignment generally increased pull-out resistance, while vertical misalignment produced greater restraint than horizontal misalignment at comparable angles. V6.3 was the most critical single-plane case, reaching 7.5 kN and exhibiting the most pronounced distress. The combined case showed multidirectional interaction rather than a simple additive response. The H3.1 specimen experienced premature movement due to inadequate lateral restraint; consequently, it was treated as experimentally compromised and excluded from quantitative model validation and interpretation of the misalignment trend.

Table 1: Experimental and finite element peak pull-out loads.

Specimen	Misalignment	Exp. (kN)	FEM (kN)
C0	Aligned	0.90	1
H3.1*	Horizontal, 3.1°	0.60	4.6
H6.3	Horizontal, 6.3°	4.50	5.2
V3.1	Vertical, 3.1°	2.40	2.6
V6.3	Vertical, 6.3°	7.50	7.8
C3.1	Combined	2.20	3.1

*H3.1 was affected by inadequate lateral restraint and excluded from quantitative model validation.

Excluding H3.1, the FEM reproduced the principal experimental response. Absolute peak-load errors were 11.1% for C0, 15.6% for H6.3, 8.3% for V3.1, and 4.0% for V6.3. The combined C3.1 case showed a larger error of 40.9%, indicating that the model represented the single-

plane response more reliably than the multidirectional interaction. Numerical results also identified localised stress and tensile damage around the dowel-concrete interface, with V6.3 showing the strongest concentration, consistent with the severe experimental distress.

4. Conclusions

Dowel misalignment significantly affected pull-out resistance and local stress development in the tested thin rigid pavement joints. Vertical misalignment produced greater restraint than horizontal misalignment, with V6.3 reaching 7.5 kN and exhibiting the most pronounced distress. The FEM reproduced the valid aligned and single-plane peak loads within 4.0-15.6% and identified concentrated tensile damage around the dowel-concrete interface. The absence of replicate testing limits statistical assessment of experimental variability. From a practical perspective, the results indicate that vertical angular misalignment requires particular attention during dowel installation because increased restraint and localised damage can restrict joint movement and contribute to premature joint deterioration. The findings support improved construction control of dowel alignment in thin rigid pavements.

References

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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF DOWEL BAR MISALIGNMENT IN THIN RIGID PAVEMENT JOINTS

Problem

Dowel bar misalignment at transverse joints **reduces load transfer efficiency** and can cause **high stresses and cracking** in concrete pavements.

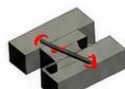
Misalignment Types



Vertical Skew
(Section View)



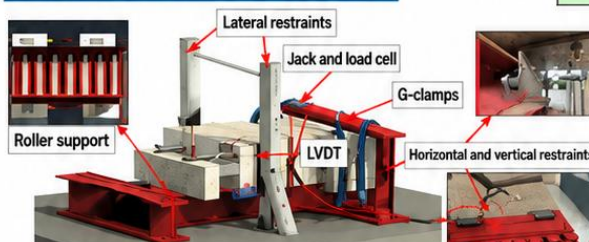
Horizontal Skew
(Plan View)



Combined Skew
(3D View)

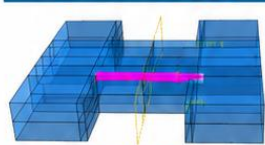
Test ID	Misalignment Type	Magnitude
C0	Control (Perfect Alignment)	0°
V 3.1	Vertical Skew	3.1°
V 6.3	Vertical Skew	6.3°
H 3.1	Horizontal Skew	3.1°
H 6.3	Horizontal Skew	6.3°
C 3.1	Combined Skew	3.2° V + 3.2° H

Experimental Program

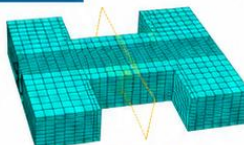


- ✓ One end debonded with grease
- ✓ Jack pull-out loading (displacement controlled)
- ✓ Load & displacement: Load cell + LVDT
- ✓ Roller plates & lateral restraints
- ✓ Tested to failure

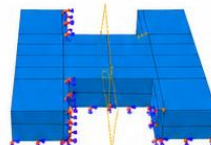
FEM Modeling



Model geometry and boundary conditions



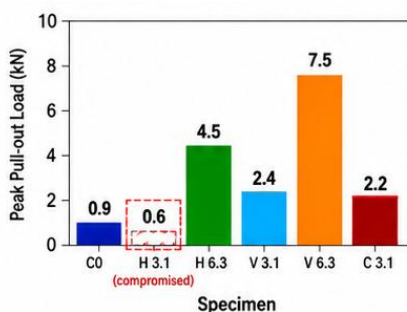
Mesh (refined near dowel)



Loading and restraints

- ✓ Concrete Damaged Plasticity (CDP)
- ✓ Dowel-concrete contact interaction
- ✓ Nonlinear static analysis
- ✓ Stress and damage evaluation

Results



Observed Concrete Distress



C0
(Aligned)



H 3.1
(Horizontal 3.1°)



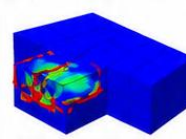
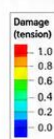
H 6.3
(Horizontal 6.3°)



V 3.1
(Vertical 3.1°)



V 6.3
(Vertical 6.3°)



FEM tensile damage
(V 6.3)



C 3.1
(Combined 3.1° + 3.1°)

Misalignment increases pull-out resistance and causes localized concrete damage, with vertical misalignment being more critical.

IMAGE PROCESSING AND MACHINE LEARNING APPROACH TO ESTIMATE TURBIDITY IN RAW WATER FOR TREATMENT PLANTS IN SRI LANKA

J.M.R.N. Ambagolla^{1*}, K.H.P. Madusanka¹, H.P.A.M. Siriwardana¹, Akarshani Amarasinghe²

¹ Department of Civil Engineering, University of Sri Jayewardenepura, Mattegoda, Sri Lanka

² Department of Computer Engineering, University of Sri Jayewardenepura, Mattegoda, Sri Lanka

**Corresponding author: rovimango@gmail.com*

Abstract

Conventional turbidity monitoring in water treatment plants requires frequent manual sampling and laboratory-based measurements, which can limit the ability to achieve continuous and cost-effective monitoring. This research developed an image-based machine learning approach for estimating raw water turbidity using digital images, evaluated as a proof-of-concept alternative monitoring method. A total of 200 raw water samples were collected from the Ambatale Water Treatment Plant laboratory, and corresponding digital images were acquired using a DSLR camera under controlled conditions. The measured turbidity ranged between 6.59 and 10.73 nephelometric turbidity units (NTU). Convolutional neural network (CNN) models were developed and evaluated using image data paired with laboratory-measured turbidity values. The results demonstrated that the improved augmented model achieved the highest prediction performance with a root mean square error (RMSE) of 0.51 and the lowest mean absolute error (MAE) of 0.374, a coefficient of determination of 0.517 as well as a Pearson correlation of 0.740, showing a moderate-to-strong agreement with measured turbidity values while reducing estimation errors compared with the initial models. Furthermore, a conceptual hardware prototype and software monitoring dashboard were developed to evaluate the practical implementation potential of the proposed approach. The study concludes that image-based machine learning can serve as a potential supporting tool for real-time turbidity monitoring in water treatment facilities; however, given the narrow turbidity range and single-plant dataset, these results can only validate a successful early proof of concept; broader datasets must be developed and tested using different plants across wider operational turbidity ranges for island-wide real-time deployment.

Keywords: Water quality monitoring, Computer vision, Real-time monitoring, Convolutional neural networks, Water infrastructure development

1. Introduction

Turbidity is a key water quality parameter that is monitored throughout the raw water treatment process including during the water intake, disinfection and coagulation-flocculation control phases [2]. Conventional turbidity monitoring in Sri Lanka relies on manual sampling and laboratory-based instruments, which are costly, time-consuming, and prone to delayed response to rapid fluctuations in water quality [1]. Automated inline sensors offer real-time monitoring, but their high cost continues to limit widespread adoption in many treatment facilities [1].

Image-based monitoring has emerged as a new and promising low-cost alternative, using digital cameras to capture variations in colour intensity that can be correlated with known corresponding turbidity levels [2]. Recent advances in machine learning, particularly

convolutional neural networks (CNNs), have further improved the accuracy of such image-based estimation methods by automatically extracting complex visual features from sample images [3,4].

Building on these advances, this study develops and evaluates the suitability of using an image-based machine learning approach for estimating water turbidity for raw water treatment plants in Sri Lanka. Specifically, it assesses the practical feasibility of implementing such a system with existing plant infrastructure and evaluates the prediction accuracy achievable using geo-specific, real-time turbidity sample images collected in a local raw water treatment plant.

2. Methodology

Site investigations and pilot testing were conducted at the Ambatale Water Treatment Plant, which established a controlled, repeatable image acquisition protocol. A total of 200 raw water samples were collected from the laboratory raw water line across 2 days of testing. For each sample, turbidity was measured three times using a calibrated Hach 2100Q portable turbidimeter and averaged to an NTU value, and a corresponding image was captured using a Nikon D3500 DSLR camera under standardised conditions (matte white background, 30 cm camera distance, 115–120 lux illumination, fixed exposure) which were determined through the pilot testing phase.

The dataset was split 160/40 for training and testing. A regression-based convolutional neural network (CNN) was developed with PyTorch and evaluated across three configurations: ML1 (a pre-trained baseline model), ML2 (retrained on the new dataset), and ML3 (retrained with augmentation consisting of rotation, brightness/contrast adjustment, and cropping), which artificially expanded the training set to 640 images. Each CNN consisted of stacked convolutional and pooling layers for feature extraction followed by fully connected layers producing a continuous NTU output. For ML2 and ML3, multiple epoch settings (25, 50, 100, 200 and 500 for ML2; 25, 50 and 100 for ML3) were tested, and the best-performing configuration was selected by comparing MAE, RMSE, R^2 , Pearson correlation and residual analysis on the 40 held-out test images. A preliminary hardware and dashboard feasibility concept was also created.

3. Results and Discussion

The final dataset consisted of 200 raw water samples drawn from the Kelani River intake, spanning a turbidity range of 6.59–10.73 NTU.

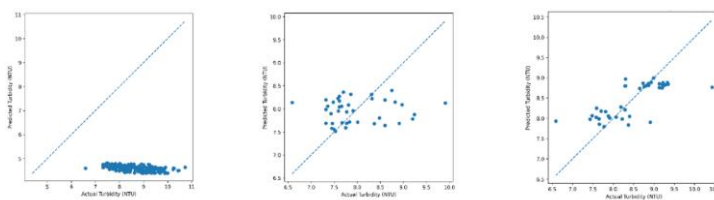


Figure 1: Predicted versus actual turbidity for ML1 (left), ML2 (middle) and ML3 (right).

As seen in Figure 1, when applied to this dataset, the pre-trained baseline model (ML1) generalised poorly as predictions fell substantially below measured values, reflecting a

systematic bias and producing a root mean square error (RMSE) of 4.174. Re-training a model directly on the newly collected samples (ML2, 25 epochs) brought the RMSE down to 0.697, though this and most other ML2 configurations produced negative R^2 values and weak Pearson correlations, indicating that predictions tend to be compressed toward the mean. The strongest

performance came from the augmented model (ML3) as shown in Figure 1, which achieved the lowest RMSE (0.510) and mean absolute error (0.374), together with a positive coefficient of determination (0.517) and moderate-to-strong Pearson correlation (0.740). These results indicate that augmenting a limited image dataset substantially improves CNN robustness and predictive accuracy.

Beyond model performance, a conceptual monitoring system was designed to translate these results into a deployable tool. A preliminary hardware enclosure was modelled using Fusion CAD software. This hardware concept was paired with a prototype software dashboard for plant operators, which converts the CNN model's raw output into a live, interpretable data stream showing real-time turbidity estimates, running averages, and historical trend graphs as seen in Figure 2.



Figure 2: Conceptual hardware prototype (left) and software monitoring dashboard (right) for real-time turbidity estimation.

4. Conclusion

This proof-of-concept study demonstrates that CNN models, enhanced through data augmentation, can estimate raw water turbidity from digital images, achieving promising prediction accuracy with minimal systematic bias under tested conditions. The conceptualised hardware and software prototypes further support the practical feasibility of deploying this approach as a low-cost supporting tool, though not yet a validated replacement for conventional methods. Future work should expand data collection across multiple plants and operational turbidity ranges as well as validate the hardware prototype in the field.

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Image Processing and Machine Learning Approach to Estimate Turbidity in Raw Water for Treatment Plants in Sri Lanka

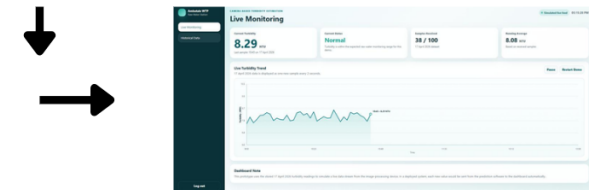
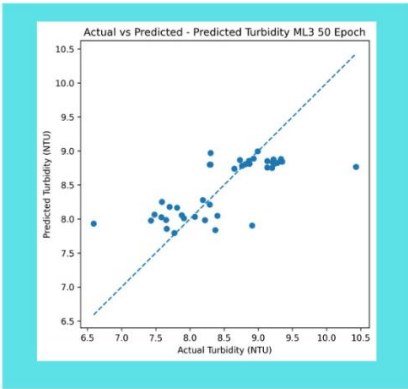
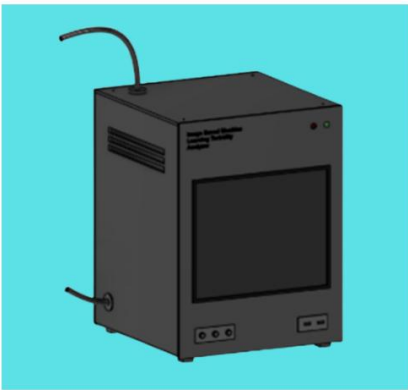
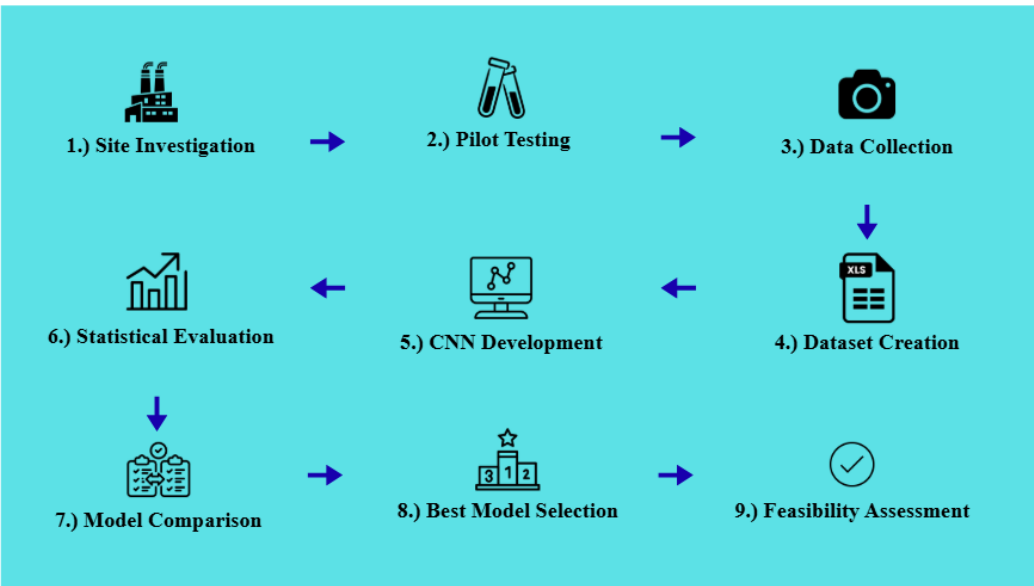


Image-based CNN model estimates raw water turbidity with accuracy, supported by a conceptual hardware and dashboard design for low-cost continuous monitoring

MULTI-DECADAL SHORELINE VARIABILITY ON THE EASTERN COAST OF SRI LANKA: CONTRASTING EROSION HOTSPOTS AND STABLE CONTROL SITES THROUGH QUANTITATIVE ASSESSMENT OF COASTAL INSTABILITY (2010-2025)

H.J. Yoosuf¹, B.C. Dissanayake^{1*}

¹ Department of Civil Engineering, Faculty of Engineering, University of Moratuwa, Sri Lanka

**Corresponding author: chaturad@uom.lk*

Abstract

Coastal erosion has emerged as a critical global challenge, yet large-scale quantitative assessments of shoreline variability remain scarce across tropical marine environments. Long-term, spatially resolved data are essential for distinguishing persistent geomorphic loss from seasonal fluctuations and for informing evidence-based coastal management strategies. This 15-year multi-decadal analysis (2010–2025) provides a quantitative assessment of shoreline variability across the Eastern Province of Sri Lanka, addressing data scarcity. Satellite imagery from Landsat and Sentinel-2 combined with automated shoreline detection reveals substantial spatial variation in coastal behaviour across the study area. Analysis of twelve coastal sites reveals distinct geomorphic patterns: six sites experience active erosion (Kalmunai, Oluvil North, Arugam Bay, Vakaraai, Passikudah, and Foul Point) with retreat rates ranging from -0.5 to -3.5 m/yr, four sites show seaward accretion (Okanda, Kattankudy, Oluvil South, and Pulmoddai) with advance rates of $+0.2$ to $+4.5$ m/yr, and two sites maintain stable geomorphic conditions (Nilaveli and Dutch Bay). These site-specific, quantified rates enable coastal managers to prioritise intervention locations and assess the effectiveness of coastal protection strategies. The methodology demonstrates how long-term satellite-derived shoreline monitoring can fill regional data gaps and provide quantitative foundations necessary for sustainable coastal zone management and informed policy decisions in data-scarce tropical regions.

Keywords: Coastal erosion, Remote sensing, Coastal zone management

1. Introduction

Coastal erosion represents a critical global crisis, with approximately 24% of the world's sandy beaches currently retreating at rates exceeding 0.5 m/year. The Eastern Coast of Sri Lanka, spanning the Trincomalee, Batticaloa, and Ampara districts, is a highly sensitive region governed by seasonal monsoonal wave action. Despite its socioeconomic importance for fisheries, settlements, and tourism, this area has historically suffered from limited long-term monitoring and data scarcity. Recent decades have revealed noticeable shoreline instability, particularly near anthropogenic structures such as Oluvil Harbour, which has physically disrupted natural sand transport and created a distinct geomorphic divide. This study quantitatively evaluates shoreline evolution across ten selected hotspots over a 15-year period (2010–2025) using publicly available satellite imagery. The research identifies a critical Southeastern Erosional Corridor and demonstrates that infrastructure development exerts a more dominant influence on sediment transport than natural coastal processes. Figure 1 shows the distribution of selected sites over the Eastern Coast of Sri Lanka.

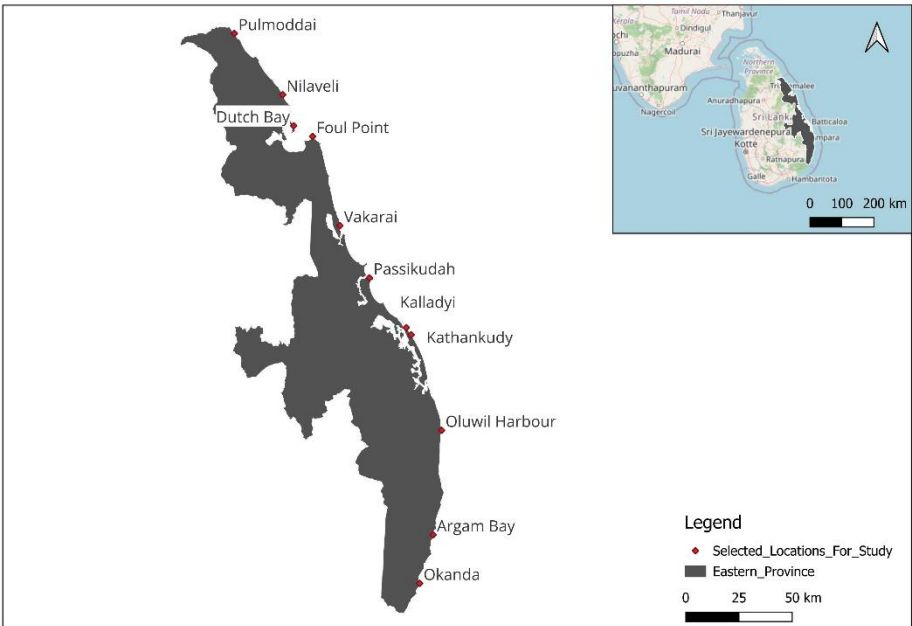


Figure 1: Selected sites for the study on the Eastern Coast of Sri Lanka.

2. Methodology

Multi-temporal satellite data were retrieved from Landsat 5/7/8/9 and Sentinel-2 constellations spanning 2010–2025, available on the Google Earth Engine API. Shoreline extraction employed the Modified Normalised Difference Water Index (MNDWI) with Otsu's thresholding method and the Marching Squares contouring algorithm for high geometric precision. This was done through CoastSat, which is an open-source Python toolkit that extracts long-term shoreline-- change data from satellite imagery (Landsat and Sentinel-2), enabling coastal scientists and engineers to analyse beach- erosion, accretion, and slope dynamics worldwide. Shoreline change rates were computed using Linear Regression Rate (LRR) analysis, while Pearson correlation coefficients and p-values distinguished permanent geomorphic trends from seasonal variability.

3. Results

Six coastal sites experience erosion (Table 1) at rates ranging from −0.1 to −3.5 m/yr, with the Southeastern Erosional Corridor (Kalmunai to Karativu) showing the most severe retreat (−2.8 to −3.5 m/yr). Four sites show accretion at +0.2 to +4.5 m/yr, notably at Oluvil South (+4.5 m/yr), while Oluvil North experiences erosion (−1.2 to −1.8 m/yr), confirming infrastructure-induced sediment disruption ($r = 0.23\text{--}0.33$). Two sites (Nilaveli and Dutch Bay) remain nearly stable at 0.05 m/yr, establishing baseline conditions for the region.

Table 1: Shoreline change rates (m/year) in selected sites.

District	Site	Rate (m/year)	Analysis
Ampara	Kalmunai to Karativu	−2.8 to −3.5	Erosion
	Oluvil (North)	−1.2 to −1.8	Erosion
	Oluvil (South)	+4.5	Accretion
	Arugam Bay	−1.2	Erosion

	Okanda	+0.2 to +0.4	Accretion
Batticaloa	Kattankudy	+0.8 to +1.5	Accretion
	Vakarai	-0.1 to -0.3	Erosion
	Passikudah	-0.1 to -0.2	Erosion
Trincomalee	Pulmoddai	+0.1 to +0.2	Accretion
	Nilaveli	0.05	Stable
	Dutch Bay	0.05	Stable
	Foul Point	-0.1	Erosion

4. Discussion and Recommendations

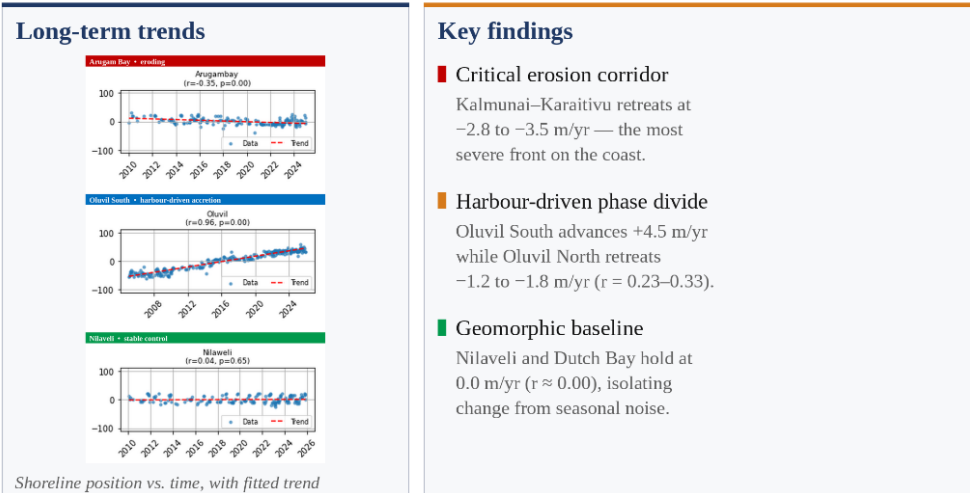
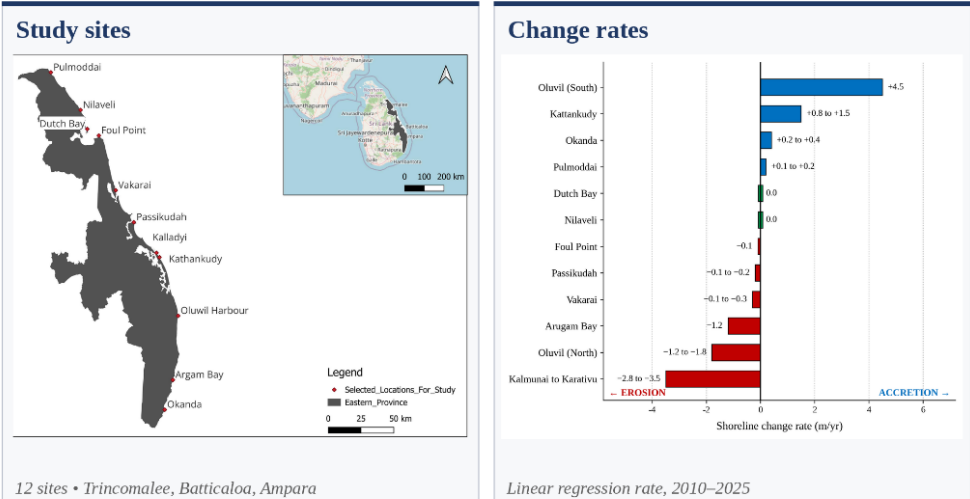
The results unambiguously demonstrate that anthropogenic interventions exert far greater influence on shoreline dynamics than natural processes alone. Critical management interventions include: (1) immediate implementation of mechanical sand bypassing systems at Olivil Harbour to restore natural sediment continuity; (2) hybrid approaches combining hard structures and beach nourishment in the Southeastern Erosional Corridor; and (3) continuous satellite monitoring of Nilaveli and Dutch Bay as geomorphic benchmarks. These site-specific strategies are essential to achieve sustainable coastal stability and integrated sediment management.

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Distinguishing Erosion Hotspots from Stable Control Sites

Multi-decadal shoreline variability, Eastern Sri Lanka (2010–2025)



Engineering infrastructure exerts greater influence on sediment dynamics than natural processes

Method

Landsat 5/7/8/9 and Sentinel-2 imagery • MNDWI shoreline extraction (CoastSat)
Linear regression rate • Pearson correlation and significance testing

Erosion

Accretion

Stable control

OPTIMISING SENTINEL-1 BACKSCATTER THRESHOLDS FOR SURFACE WATER MAPPING IN SMALL IRRIGATION TANKS: A GOOGLE EARTH ENGINE WEB APPLICATION FOR TANK WATER MANAGEMENT

Avintha Senavirathne^{1*}, B.C. Dissanayake¹, L.N. Gunawardhana¹, R.L.H.L. Rajapakse¹

¹ UNESCO Madanjeet Singh Centre for South Asia Water Management (UMCSAWM), Department of Civil Engineering, University of Moratuwa, Moratuwa, Sri Lanka

**Corresponding author: avintha.geo@gmail.com*

Abstract

Small irrigation tanks are essential structures for water management in the dry zone of Sri Lanka, yet consistent time-series observations of their surface-water extent remain scarce. This study develops and assesses optimised Sentinel-1 backscatter thresholds for surface-water mapping, implemented on the Google Earth Engine platform and demonstrating its application at Eru Wewa in the Malwathu Oya River Basin. The model was calibrated using reference points collected on 30 March 2021 by testing VV, VH, and VV–VH threshold combinations and selecting the combination with the highest overall accuracy and Kappa coefficient. The optimal thresholds were negative 17 dB for VV, negative 35 dB for VH, and 14 dB for the VV minus VH difference. The calibrated model achieved an overall accuracy of 95% and a Kappa coefficient of 0.894. Independent reference points from 3 December 2021 and 22 August 2025 gave overall accuracies of 90% and 90% with Kappa coefficients of 0.807 and 0.800, respectively. The estimated water-surface areas were validated on three dates, with a consistent underestimation of between 6% and 15%. The water-surface-area time series from 1 January 2020 to 30 November 2024 was analysed alongside seasonal rainfall to assess the temporal response of the reservoir. The workflow was further developed into a user-friendly web application that generates water-extent time series and converts them into storage based on the area-capacity curve, following the depth-area-storage capacity relationships for village tanks lacking surveyed bathymetric data. The application demonstrates practical reservoir monitoring at Eru Wewa, while broader applicability requires multi-site validation.

Keywords: Dry zone reservoirs, Radiometric thresholding, Remote sensing, Synthetic aperture radar, Village tank cascade systems

1. Introduction

Small irrigation tanks play an important role in water storage and agricultural water management in the dry zone of Sri Lanka [1]. However, temporal variations in their surface water extent are not routinely observed. Satellite remote sensing provides an effective means of monitoring reservoir surface-water dynamics over time [2], including relatively small water bodies [3]. Optical indices such as the Normalised Difference Water Index are widely used for this purpose, but their reliance on cloud-free acquisitions limits observation frequency during the monsoon periods when tank levels change most rapidly, whereas Sentinel-1 synthetic aperture radar acquires data independently of cloud cover and illumination. Therefore, this study aims to optimise Sentinel-1 backscatter thresholds for accurately mapping surface water in small irrigation tanks, using Eru Wewa in the Malwathu Oya River Basin as a case study.

2. Methodology

Sentinel-1 synthetic aperture radar (SAR) imagery was processed in Google Earth Engine, which enables large-scale geospatial analysis and time-series processing [4]. VV and VH backscatter were filtered and used together with the VV minus VH backscatter difference. Multiple threshold combinations were evaluated using reference samples from 30 March 2021. The selected thresholds were independently validated using reference samples from 3 December 2021 and 22 August 2025. Water-surface areas were subsequently compared with Google Earth reference delineations, and a time series from January 2020 to November 2024 was analysed together with daily rainfall. The calibrated workflow was implemented as a Google Earth Engine web application. The user selects a tank boundary and date range, and the application applies the optimised thresholds to every Sentinel-1 acquisition in that period, returning a water-surface-area time series as a chart and classified maps. Mapped areas are interpolated on the tank's area–capacity curve proposed by Imbulana (2022), to give a paired storage time series without any local processing.

3. Results and Discussion

Sentinel-1 is a C-band SAR mission developed by the European Space Agency (ESA) under the Copernicus Programme. It provides all-weather, day-and-night imagery with approximately 10 m spatial resolution and a nominal revisit time of 6–12 days. The optimal thresholds were negative 17 dB for VV, negative 35 dB for VH, and 14 dB for the VV minus VH difference. The model achieved an overall accuracy of 95% and a Kappa coefficient of 0.894, while independent validations achieved 90% and 90% accuracy, confirming reliable Sentinel-1 water classification. The spatial classification results are shown in Figure 1.

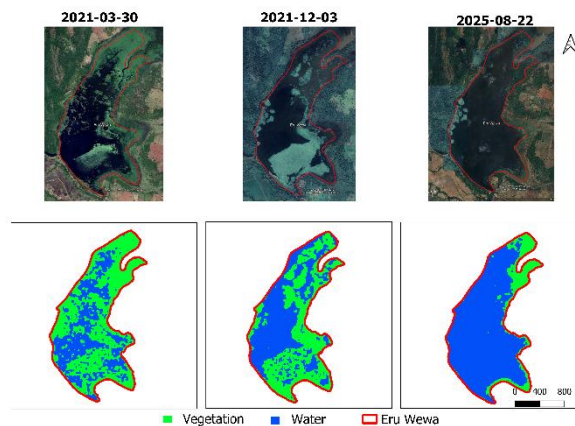


Figure 1: Sentinel-1 water and aquatic vegetation for calibration (30 March 2021) and validation (3 December 2021 and 22 August 2025).

Sentinel-1 underestimated the reference water areas by 6% to 15% (Table 1), potentially due to shoreline vegetation, shallow water, and mixed-pixel effects [3].

Table 1: Comparison of reference and Sentinel-1-derived water-surface areas.

Date	Google Earth reference area (ha)	Sentinel-1 classified area (ha)	Difference (ha)	Relative difference (%)
30 Mar 2021	94.56	83.25	11.31	12
03 Dec 2021	130.75	111.15	19.60	15
22 Aug 2025	195.00	182.66	12.34	6

The 2020 to 2024 time series (Figure 2) showed substantial seasonal variations in water-surface extent that generally corresponded with seasonal rainfall variability.

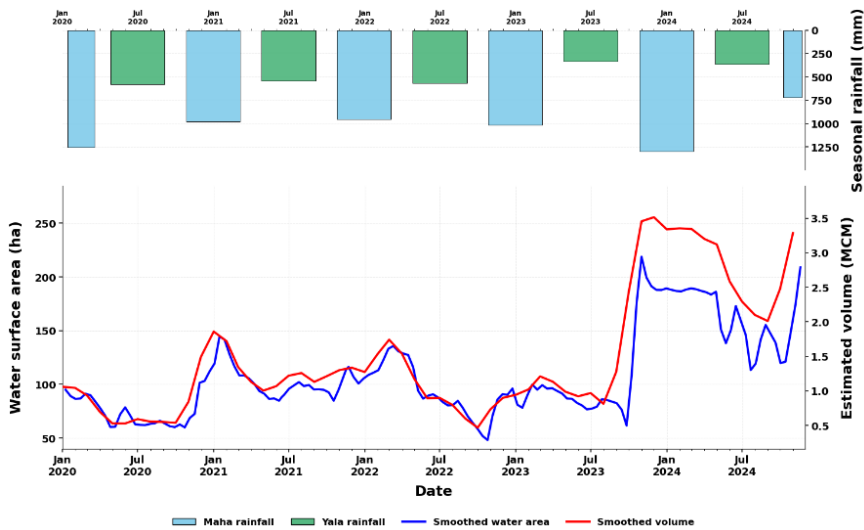


Figure 2: Seasonal rainfall, water-surface area, and estimated reservoir volume variation in Eru Wewa, 2020 to 2024.

4. Conclusion

The study demonstrates that an optimised Sentinel-1 threshold approach can provide consistent multi-temporal estimates of water-surface extent in a small irrigation reservoir. Independent validation confirmed good classification performance, although a systematic underestimation of surface-water area was observed. The temporal variation of rainfall, water-surface area, and estimated storage exhibited similar seasonal patterns. The workflow was implemented as a Google Earth Engine application for generating water-area and storage time series. Further validation using concurrent field observations is recommended.

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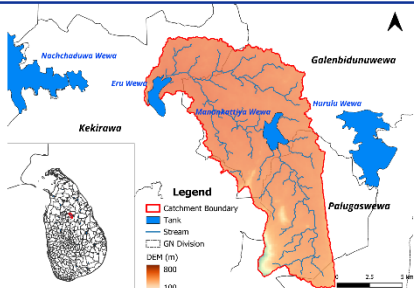
Optimizing Sentinel-1 Backscatter Thresholds for Surface-Water Mapping in Small Irrigation Tanks: A Google Earth Engine Web Application for Water Management

Demonstrated at Eru Wewa — a small dry-zone irrigation tank, Sri Lanka

01 STUDY AREA & CONTEXT

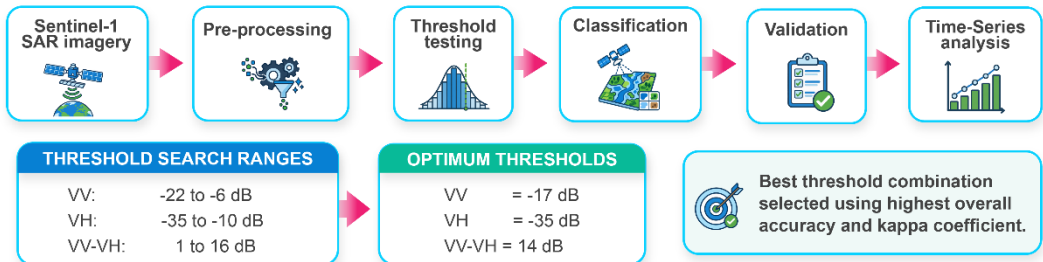


Eru Wewa, Sri Lanka



Small irrigation tank
Dry-Zone water management

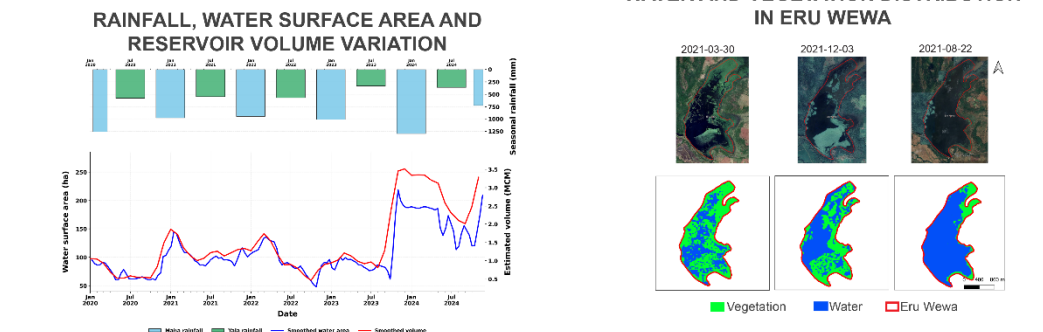
02 METHODOLOGY WORKFLOW



03 VALIDATION & RESULTS

ACCURACY ASSESSMENT			REFERENCE VS CLASSIFIED WATER AREA			
Calibration 30 Mar 2021	Validation 03 Dec 2021	Validation 22 Aug 2025	Date	Google Earth (ha)	Sentinel-1 (ha)	Difference (%)
OA 94.74%	OA 90.48%	OA 90.00%	30 Mar 2021	94.56	83.25	11.96%
Kappa 0.894	Kappa 0.807	Kappa 0.800	03 Dec 2021	130.75	111.15	14.99%
			22 Aug 2025	195.00	182.66	6.33%

04 TEMPORAL RESPONSE (01 Jan 2020 - 30 Nov 2024)



05 KEY OUTCOME



Optimized Sentinel-1 thresholds deliver consistent, cloud-independent estimates of surface-water extent and storage for small irrigation tanks, delivered through a Google Earth Engine web application for day-to-day tank water management.



ENFORCING CATCHMENT WATER BALANCE IMPROVES THE RELIABILITY OF NEURAL STREAMFLOW PREDICTION IN TROPICAL CATCHMENTS

Zafar Aqthaf¹* and Lalith Rajapakse¹

¹ Department of Civil Engineering, University of Moratuwa, Katubedda, Sri Lanka

*Corresponding author: aqthafahz.21@uom.lk

Abstract

Reliable streamflow prediction underpins flood early warning and water-resource planning, yet remains difficult in tropical catchments where monsoonal extremes and sparse monitoring limit both process-based and data-driven models. Data-driven models post high skill scores, but by minimising only statistical error they can produce hydrographs that silently violate the catchment water balance, generating runoff unsupported by rainfall. This study asks whether physical consistency, not accuracy alone, should rank such models. A compact neural network constrained to honour a lumped water-balance relation was tested on two contrasting Sri Lankan basins, a perennial wet-zone basin and a regulated intermittent dry-zone basin, against a process-based model and four deep-learning baselines. In the wet-zone basin the constrained model was both the most accurate and the most mass-conserving. In the dry-zone basin the highest Nash–Sutcliffe efficiency belonged to a model overpredicting runoff volume by about twenty percent, whereas the constrained model held volumetric bias near six percent with the best Kling–Gupta efficiency. Conventional efficiency scores can thus mask implausible predictions; embedding mass conservation is an auditable reliability safeguard for operational hydrology.

Keywords: Hydrological modelling, Physics-informed machine learning, Mass conservation, Kling–Gupta efficiency

1. Introduction

Floods and droughts are among the costliest natural hazards, and dependable streamflow prediction underpins flood early warning, reservoir operation, and irrigation scheduling. Prediction is hardest in tropical monsoon settings of intense seasonal rainfall and sparse gauging. Process-based models demand dense data and laborious calibration rarely available in developing regions, whereas data-driven models learn non-linear rainfall-runoff behaviour directly from records and now dominate the literature [1]. Their strength is also their weakness: minimising only statistical error, they carry no guarantee of physical consistency and can overfit dominant regimes, degrading beyond the training distribution [2]. A model may reproduce a hydrograph's shape while generating water no rainfall supports, a failure conventional skill scores do not reveal.

Physics-informed neural networks instead constrain learning with domain knowledge, embedding governing equations directly in the training loss so predictions stay physically admissible [3]. The decisive question for operational deployment is not which model attains the highest efficiency score, but which respects conservation of mass. Nash–Sutcliffe efficiency, the default ranking metric, overweights high-flow fit and can hide systematic volume error, exactly what decomposed and volumetric metrics were designed to expose [4]. This study therefore reframes evaluation around physical consistency, testing a water-balance-constrained network on two hydro-climatically opposite Sri Lankan basins.

2. Materials and Methods

Two basins spanning Sri Lanka's hydro-climatic extremes were used. The Kalu Ganga (wet zone; ~2,719 km²; 4,000-5,000 mm yr⁻¹; south-west monsoon; 2001-2010) is perennial and flood-prone; the Maduru Oya (dry zone; ~1,487 km²; ~2,158 mm yr⁻¹; north-east monsoon; 2006-2015) is intermittent and regulated by an irrigation-tank cascade. Daily precipitation, temperature, evaporation, and discharge were quality-controlled, gap-filled, and reduced to a common 19-feature set of antecedent-rainfall and cyclical-seasonality predictors, split chronologically 70/30 into calibration and validation. Treating the catchment as a single control volume, continuity with a linear-reservoir closure gives a first-order discharge relation [5]:

$$dQ/dt = \alpha_p \bar{P} - \alpha_e E - \beta Q + \delta$$

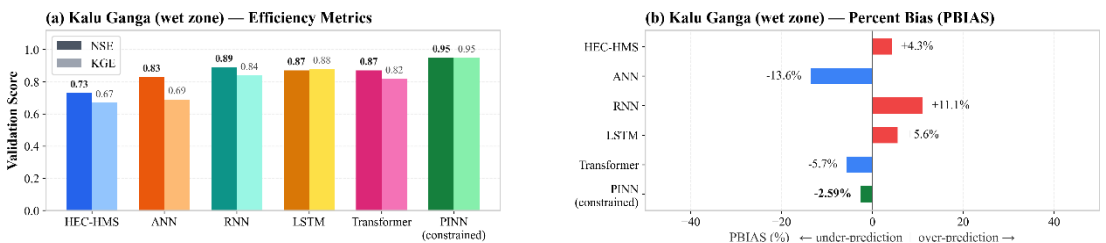
where the precipitation, evaporation, and recession coefficients are constrained non-negative to stay physically admissible. The residual was evaluated using daily finite differences, with learned coefficients representing effective basin responses rather than directly measurable parameters. The training loss of a compact feed-forward network (~11,000 parameters, with a linear skip connection) summed the streamflow prediction error and this water-balance residual, the residual weighted by a penalty coefficient ramped from near-zero over a warm-up so the network first fit the hydrograph before conservation was enforced. The process-based HEC-HMS was calibrated over the same periods and splits as the deep-learning baselines (ANN, RNN, LSTM, Transformer). Skill used Nash–Sutcliffe (NSE) and Kling–Gupta (KGE) efficiencies, the volumetric KGE component, and percent bias (PBIAS), the last two chosen to expose water-balance error that NSE can mask [4].

3. Results and Discussion

Wet zone, where accuracy and consistency agree. In the perennial Kalu Ganga the constrained network was best on every criterion (Figure 1), reaching validation NSE and KGE of 0.95 at only -2.6% volumetric bias; enforcing mass conservation cost nothing.

Regulated dry zone, where they diverge. In the tank-regulated Maduru Oya the LSTM ranks first by NSE (0.68) yet overpredicts runoff volume by ~20% (PBIAS = +20%, $\beta = 1.20$), manufacturing water unsupported by rainfall; HEC-HMS underpredicts by 37%. The constrained network ranks third by NSE (0.60) but gives the lowest absolute bias (+6%) and highest KGE (0.72), so the NSE leaderboard is physically misleading: the apparently best model is the least credible for water allocation.

A transferable reliability safeguard. The same architecture generalised across both regimes without basin-specific tuning, so the water-balance term supplies transferable regularisation. Its limitation is instructive: in the dry-zone basin it attenuated flash peaks to ~64% of observed magnitude while keeping recession and volume consistent, because the single-reservoir closure cannot capture threshold tank-spilling (Figure 2), an honest, interpretable failure rather than a hidden one.



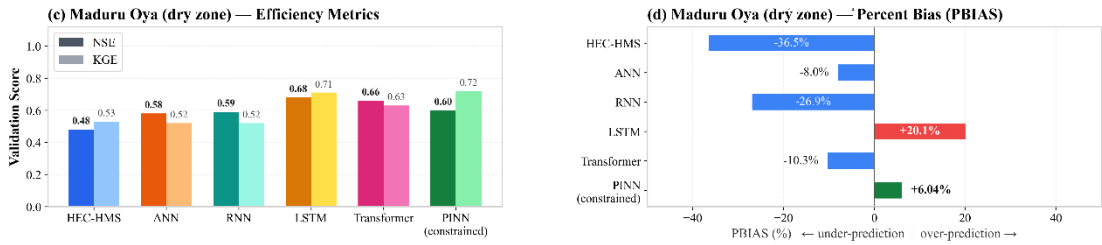


Figure 1: Validation NSE, KGE, and PBIAS for all models in both basins.

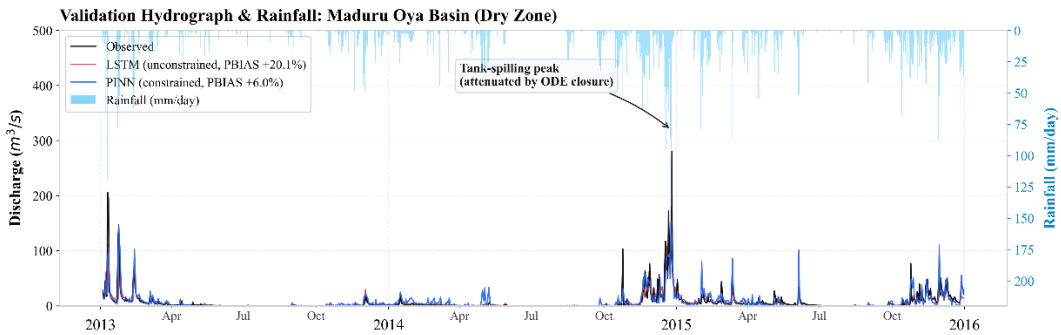


Figure 2: Observed vs. predicted daily discharge for the dry-zone validation period.

4. Conclusions

Reframing evaluation around physical consistency materially improves neural streamflow prediction in tropical basins: where accuracy and consistency agree the constrained model was best on all metrics; where they diverge it preserved the mass conservation that the highest-efficiency model silently violated. Mass conservation should therefore be a first-class evaluation criterion, reported through volumetric and decomposed metrics, a light, auditable safeguard for operational water management in data-scarce regions. The dry-zone behaviour further suggests that the physical constraint need not use the same response structure in every basin. Perennial flow can be represented by a smooth storage-response prior, whereas intermittent or strongly regulated systems may benefit from regime-aware response functions for dry-period persistence and rapid event activation. As the framework uses contemporaneous observed forcing, its immediate role is continuous simulation and planning support rather than lead-time flood forecasting.

References

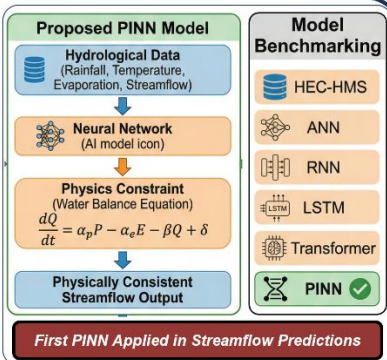
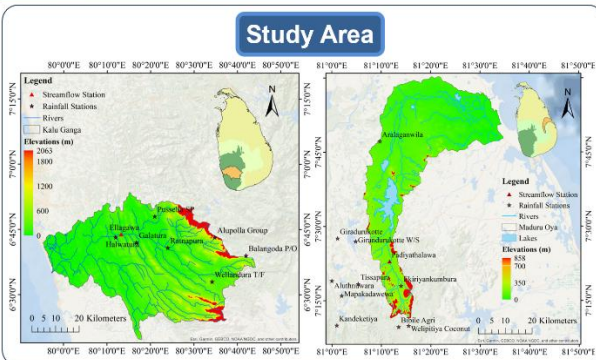
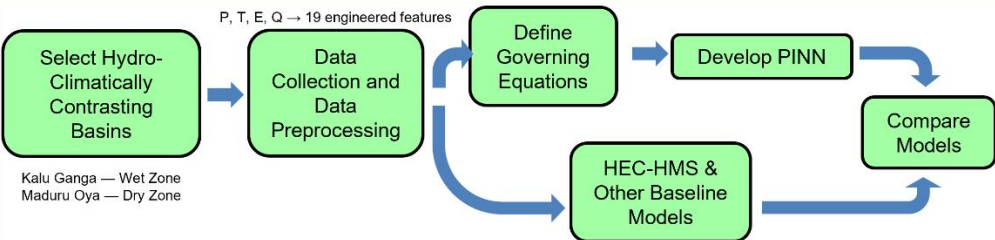
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ENFORCING THE WATER BALANCE FOR RELIABLE NEURAL STREAMFLOW PREDICTION
IN TROPICAL CATCHMENTS

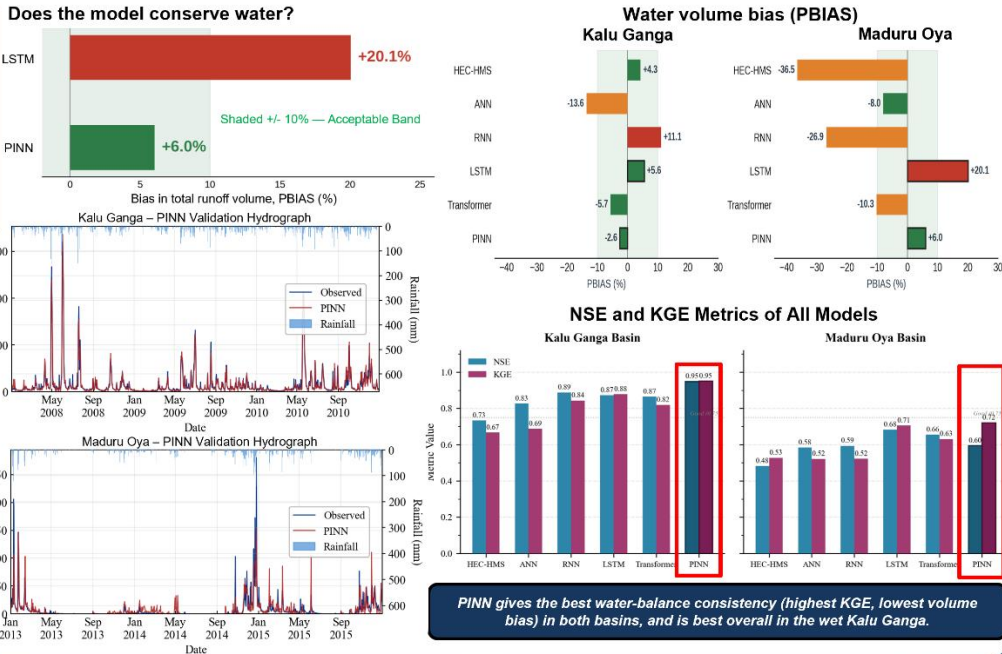
Aim

To test whether embedding the catchment water balance makes neural streamflow prediction physically reliable, not just accurate, across a wet and a dry tropical basin

Methodology



Results



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