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EDITORIAL PANEL – YEAR 2026

The Editor welcomes manuscripts, articles, photographs and advertisements for consideration. Manuscripts, articles and photographs will be published free of charge if they are in acceptable quality while a fee will be charged for advertisements at the rate of Rs. 150.00 per square centimetre. All manuscripts will be subjected to Double blind peer review process before the acceptance for the publication.

EDITOR'S MESSAGE

"Role of structural engineers after the disaster of Cyclone Ditwah"

It is indeed a privilege for me to be reappointed as the Editor of SSESL following the completion of the term of Emeritus Professor S. M. A. Nanayakkara. He rendered an invaluable service during his tenure by significantly uplifting the standards of Modulus and other SSESL publications. I sincerely hope to continue this legacy by following in his footsteps.

At the same time, Sri Lanka is currently at a critical juncture in the aftermath of Cyclone Ditwah, which is estimated to have caused damages exceeding US$ 4.0 billion. In this context, the role of structural engineers is crucial, both in immediate recovery efforts and in long-term reconstruction. A large number of SSESL members have been actively involved in reconstruction and strengthening projects of critical infrastructure since the onset of this tragic event, contributing in various professional capacities. Their dedicated efforts enabled the rapid restoration of essential services such as electricity, water supply, and road networks, despite the widespread devastation. These contributions deserve the highest appreciation.

Notably, all major dams and most of the main bridges withstood the extreme flooding caused by Cyclone Ditwah. Even in cases where bridges failed, the primary causes were embankment erosion and excessive river flow rates, which likely due to the exceedance of the original design hydrological parameters of such structures. The survival of most structures stands as clear evidence of the high design standards upheld by Sri Lankan structural engineers to ensure structural integrity under extreme conditions.

Nevertheless, this disaster also presents valuable lessons. One key aspect is the need for comprehensive stability analyses of foundations of critical structures that may be vulnerable to earth slips and embankment erosion. Failures of certain power transmission towers along major distribution lines near riverbanks have been attributed to such effects during extreme river flows. Another important concern is the impact of debris carried by floodwaters on bridges, which warrants further investigation through an integrated and multidisciplinary approach to enhance the safety of such critical infrastructure during future extreme events.

Beyond major infrastructure, the affected general public also looks to the engineering profession for assistance in restoring their homes and other essential structures damaged by this event. As structural engineers, we have a collective responsibility to extend our professional expertise generously and promptly, supporting the rebuilding of communities and infrastructure as part of our corporate and social responsibility to the nation.

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ACKNOWLEDGEMENT

The Editor wishes to thank authors of the research article and Talawakelle Tea Estates PLC for providing the photograph for the Cover Story.

CONTENT

EVENT CALENDAR – 2026

Month	Date	Event
January	27th	Question Time
February	24th	Question Time
March		Design Course 1: Steel Design to EC 3
	24th	Seminar 1
	31st	Question Time
April	28th	Question Time
May	26th	Question Time
June		Design Course 2: Multi Storied building Design to Euro codes
	30th	Question Time
July	28th	Question Time
August	18th	Annual Session
September	29th	Question Time
		Design Course 3: High Rise Building Design
October		Seminar 2
	27th	Question Time
November	25th	Question Time
December	08th	Annual General Meeting

COVER STORY

Talawakelle Tea Estates PLC, a pioneer in Sri Lanka's plantation sector, has introduced the Kiruwanaganga Tea Factory as a landmark development in sustainable tea production. Located within the Kiruwanaganga tea estate in Kirillapone, Matara - Sri Lanka.

In recognition of its sustainability performance, the Kiruwanaganga Tea Factory was awarded the Green SL® Gold rating at the annual Green Building Awards ceremony. With this achievement, it has become Sri Lanka's first green-rated tea factory, setting a new benchmark for low-carbon and responsible manufacturing in the tea industry.

The facility has been delivered as a structural steel warehouse-type industrial building, selected to enable efficient construction, long-span working areas, and flexible internal layouts suited to tea processing operations, while also facilitating future modifications or capacity expansions with minimal disruption. The key project details are summarised below:

Client – Talawakelle Tea Estates PLC
Project Manager – Hayleys project consultants
Architectural, Civil & Structural Consultant – HG Associates (Pvt) Ltd.

Type of Development – Tea factory
Sustainability Certification – Green SL® Gold (Green-rated tea factory)
Site Area – 1,123 sqm
Building Footprint – 1,747 sqm
Total Developed Area – 2,870 sqm
Total Project Value – Rs. 710 Mn

Photograph: Kiruwanaganga Tea Factory

Seminar 2 – 2025
Transforming Structural Engineering with AI and Emerging Technologies.

The second seminar for the year was held on 18th of November 2025, at Cinnamon Grand, Colombo. The event was sponsored by Melwa Conglomerate. This seminar addressed a timely topic and generated strong interest among participants. The speakers highlighted how the structural engineering is rapidly transforming through the adoption of Artificial Intelligence and other emerging technologies.

Following the lighting of the oil lamp, the President of SSESL, Eng. Ananda Senerath, made the opening remarks and welcomed the participants. The morning session was chaired by Prof. Chinthaka Mallikarachchi, while the evening session was chaired by Prof. Kushan Wijesundara. There were three presentations in the morning session. The first presentation was delivered by Prof. Nuwan Kodagoda, on Reimaging structural engineering in the age of AI. It was followed by a presentation on Data Analytics and Data Visualization for engineering by Prof. Asoka Perera. Dr. Dammika Abeykoon and Eng. Pubudu Ranawaka did a presentation on AI in structural health monitoring and LIDAR-Drone- BIM integration for intelligent structural assessment as the last presentation for the morning session. The Q & A session at the end of the session provide an opportunity to participants to directly clarify their doubts from presenters on respective presentations.

Afternoon session was also comprised of three presentations. Prof. Roshan Godliyadda discussed about AI driven multidisciplinary research and development: Transforming engineering landscape in his presentation. The second presenters, Prof. Parakram Ekanayake did his presentation on Generative AI in research and data analytics. As the last presentation of the session, Dr. Kanishka Chandrathilaka and Dr. Samiru Gayan delivered their presentation on Recent advancements in Machine Learning and their applications in structural engineering. An productive Q & A sessions was conducted at end of the session with the moderation of the session chairperson. Eng. Aravinda Kalugaldeniya , Chairman of the organizing committee delivered the vote of thanks to conclude the event.

This seminar provided an excellent opportunity for members to gain insight into the evolving professional landscape and to understand how practicing engineers must adapt to AI technologies in structural engineering applications.

Photograph 1: Lighting of the oil lamp and welcome speech

Photograph 2: The participants at the seminar

Photograph 3: Resource Persons - Morning Session: Prof. Asoka Perera, Prof. Nuwan Kodagoda, Dr. Dammika Abeykoon and Eng. Pubudu Ranawaka.

Photograph 4: Resource Persons - Evening Session: Prof. Roshan Godaliyadda, Prof. Parakrama Ekanayake, Dr. Kanishka Chandrathilaka and Dr. Samiru Gayan.

Photograph 5: Q & A and Panel Discussion – Morning Session

Photograph 6: Q & A and Panel Discussion – Evening Session

Photograph 7: Eng. Aravinda Kalugaldeniya delivering the vote of thanks.

Annual General Meeting - 2025

32nd Annual General Meeting of the Society of Structural Engineers Sri Lanka was held on the 17th December 2025 at the Cinnamon Grand Hotel Colombo. The AGM was sponsored by Lanwa – Sanstha Cement Corporation (Pvt) Ltd. and Ceylon Steel Corporation.

Photograph 8: Eng. D.T. Rajasekaran; Hon. Secretary of the outgoing committee presenting the Annual Report.

Photograph 9: The outgoing committee 2024/2025

The outgoing president Eng. R.M. Ananda Senarath and the elected president Eng. A.S.B. Edirisinghe delivered speeches at the event. The Following Executive Committee members were elected for the year 2025/2026 at the Annual General Meeting.

Office Bearers 2025/2026	
Position	**Name**
President	Eng. A.S.B. Edirisinghe
Vice President	Eng. S.S.A. Kalugaldeniya
Immediate Past President	Eng. R.M. Ananda Senarath
Past President	Eng. (Mrs.) T.J. Jayasundara
Hon. Secretary	Eng. D.T. Rajasekaran
Asst. Secretary	Eng. A.R.M.D.N.B. Ranasinghe
Treasurer	Eng. L. Gunawickrama
Asst. Treasurer	Eng. R.S.K. Thrimavithana
Editor	Eng. (Dr.) A.M.L.N. Gunathilaka
Asst. Editor	Eng. K.A.B.P. Kuruppu
Public Relations Officer	Eng. G. Ramawickrama
Committee Members - Over 40 Years	Prof. S.M.A. Nanayakkara Eng. L.G.S.J. Edirisinghe Eng. T.D. Wijitha Kumara Eng. (Mrs.) S.M.A.L.K. Sammandapperuma
Committee Members - Below 40 Years	Eng. W.K.B.L. Kurukulasooriya Eng. P.C.J.M. Wijesena

The AGM was followed by the guest talk delivered by Dr. Lasantha Malavige, who is a visionary entrepreneur and healthcare professional who has made significant contributions to innovation, agriculture, and e-commerce in Sri Lanka. Dr. Malavige, Founder and Chairman of the Lassana Group, began his entrepreneurial journey while being a medical student at the Faculty of Medicine, University of Colombo, demonstrating exceptional leadership from an early stage.

In his session on "Entrepreneurship for Engineers", Dr. Malavige shared valuable insights on innovation-driven entrepreneurship, building sustainable enterprises, and the role of engineers in creating scalable business solutions. He emphasized leadership, adaptability, and technology-enabled growth as key drivers for success in today's competitive global environment.

Photograph 10: Dr. Lasantha Malavige delivering speech

Photograph 11: Participants at AGM

Photograph 12: More from the AGM

Every year, the Society of Structural Engineers Sri Lanka honours authors of the best paper presented at the Annual Sessions and authors of the best technical paper published in Modulus at the AGM. Accordingly, the Prof. Raghu Chandrakeerthi Award for the Best Paper presented at the Annual Sessions and the Access Engineering Award for the Best Paper published in Modulus for 2025 were presented for following authors at the AGM.

Best Paper Winners of Year 2025	
Annual Sessions 2025 (Prof. Raghu Chandrakeerthi Best Paper)	Mr. R S S A Wijesundara
Modulus 2025 (Access Engineering Best Paper)	Ms. Dilini Perera

Photograph 13: The Best Paper presented at the Annual Sessions 2025 - awarded to Eng. R S S A Wijesundara

Photograph 14: Cocktail and Fellowship dinner

Question Times (QT)

QT October – Fatigue Damage Assessment of Steel Structures: Concepts, Theories and Assessment Techniques

The Question Time session for the month of October was held on 28th October 2025 at 5.15pm at the Wimalasurendra Auditorium, IESL and the resource person for the event was Eng. (Dr.) P. A. K. Karunananda, Senior Lecturer, Department of Civil Engineering, The Open University of Sri Lanka. The Lanwa Steel and Lanwa Cement sponsored the event.

The fundamentals of metal fatigue and its significance in civil engineering structures subjected to cyclic loading were discussed. Eng. (Dr.) P. A. K. Karunananda explained how repeated loading can lead to fatigue failure at stress levels lower than the ultimate material capacity, emphasizing its relevance to steel structures. He further elaborated on the effects of high-amplitude cyclic loading arising from earthquakes and cyclones, highlighting the necessity of fatigue damage assessment in minimizing catastrophic structural failures.

Photograph 15: Eng. (Dr.) P. A. K. Karunananda delivering the presentation

Photograph 16: Participants in the Event

QT November – Thermal Behaviour of CFRP – Reinforced Steel and Concrete Structures under Elevated Temperatures

Eng. (Dr.) Kanishka Chandrathilaka, Senior Lecturer, Department of Civil Engineering, University of Moratuwa delivered the presentation on Thermal Behaviour of CFRP – Reinforced Steel and Concrete Structures under Elevated Temperatures in Question time session held on 25th November 2025 at 5.15 pm at the GAP auditorium, Vidya Mawatha, Colombo 07. The event was sponsored by Tokyo Cement Group.

The application of Carbon Fiber Reinforced Polymer (CFRP) composites for strengthening and retrofitting steel and concrete structures was discussed, with particular emphasis on their mechanical performance and durability advantages. Eng. (Dr.) Kanishka Chandrathilaka explained the challenges associated with the behaviour of CFRP systems under elevated temperatures, especially during fire exposures.

He further elaborated on the thermal response of CFRP-reinforced systems, highlighting material degradation, the influence of glass transition temperature, and the reduction in bond strength at high temperatures. Experimental findings and recent research outcomes were presented to illustrate how temperature affects the structural performance and failure mechanisms of CFRP-strengthened members. Strategies to enhance the fire resistance of CFRP applications in structural engineering were also discussed.

Photograph 17: Eng. (Dr.) Kanishka Chandrathilaka delivering the presentation.

Photograph 18: Participants in the Event

Outgoing President's Speech at AGM

It is truly a great honor and a privilege to stand before you today as I conclude my term as the 10th President of the Society of Structural Engineers, Sri Lanka.

I wish to express my heartfelt thanks to all members of the SSESL for electing a group of young and dynamic professionals to serve on the Executive Committee for the year ahead. I remain confident in the bright and promising future of the Society of Structural Engineers, Sri Lanka.

We have a significant task ahead of us as engineers—particularly as structural engineers. Our focus must now shift toward the rehabilitation and resettlement phase following the recent disaster. There is a clear and growing need for coordinated professional and technical contributions.

In this context, your observations regarding the potential role of SSESL are both timely and highly pertinent. With its broad and diverse pool of expertise, SSESL is well positioned to make a meaningful contribution—especially in areas such as affordable, resilient, and prefabricated housing solutions. Through this, we can effectively complement the efforts of relevant government institutions and other key stakeholders.

When I reflect on the past twelve months, I can say with confidence that it has been a dynamic—and at times demanding—year. We have moved through a rapid succession of important events and challenges, each calling for adaptability, teamwork, and a shared commitment to our profession. I am proud of how we have responded together.

First and foremost, I wish to acknowledge the exceptional engagement of our Executive Committee. Their dedication and commitment have been central to driving the core objectives of the Society. The responsibilities we carry demand integrity, technical competence, and a wide range of expertise—and throughout this year, the Executive Committee has exemplified these qualities.

I would also like to express my sincere gratitude to my colleagues and peers who have supported me throughout this journey. Your guidance, encouragement, and cooperation have meant a great deal to me, both personally and professionally

Our sponsors have played a pivotal role in the Society's success this year. I extend my heartfelt thanks to each of them for their unwavering support. Their commitment enabled us to expand our plans beyond what we initially envisaged, resulting in the successful organization of 10 QT's, An Annual Sessions, Two Full day high quality seminars, well attended Two design Courses. I will have to thank our Editorial team headed by Prof Anura Nanayakkra for their dedication in publishing four "Modulus" during the year 2025.These contributions have had a meaningful impact on our activities and on the value, we deliver to our members.

I would also like to once again thank Eng. Tharangika Jayasundera, Eng. Srilal, Eng. Sahabandu, Eng. Nandana Abeysuriya, and Eng. Rajasekaran for the initiative taken in relation to the development of building codes for the World Bank. We are now working closely with NBRO in preparing the Terms of Reference for the next stage of national building code development. Which is must needed at the juncture.

Recently, we conducted a course on Eurocode 7 with the kind assistance of Prof. Kushan Wijesundara of the University of Peradeniya. We initiated a project by our Ex-Co member Gamini Ramawickrama and to collect data and map geotechnical data, beginning with the Colombo District.

I must not forget three young council members Eng Bandhuka Kuruppu, Eng Damitha Ranasinghe, Eng Neomal Ferdinando for their untiring contribution in arranging QT's, Seminars, Annual session and publishing "Modulus".

I must also recognize the hard work and dedication of the SSESL Secretariat staff (Dilki and Hashan). Their untiring efforts and invaluable behind-the-scenes support throughout the year deserve our sincere appreciation.

I trust that the Annual Report, presented earlier by our Honorary Secretary, has clearly conveyed the scale of work undertaken by our volunteers during this term. While we can take pride in what has been achieved, there is still much more to be done.

Together with the newly appointed Executive Committee, headed by Eng. Anuruddha Edirisinghe, I remain fully committed to building on this progress and guiding the Society toward continued growth and excellence.

Finally, I thank you all for the trust, support, and cooperation extended to me during my tenure.

Thank you.

Eng. R M Ananda Senarath
BSc Eng (Hons), CEng (SL & UK), HLMIE(SL), MICE(UK),
FSSE(SL), M Cons E(SL),
President 2024/2025

President's Speech at AGM

It is with great pride, humility, and a deep sense of responsibility that I accept my election as the President of the Society of Structural Engineers, Sri Lanka for the year 2026. I sincerely thank all Past Presidents, the outgoing and newly elected Executive Committee members, and all Corporate Members for the trust and confidence placed in me.

I am truly honored to serve the Society in this capacity. I assure you that I will devote my full efforts, abilities, and professional experience to further elevate SSE, SL and strengthen its role as the leading professional body for structural engineers in Sri Lanka.

I gratefully acknowledge the invaluable support and guidance extended to me by the outgoing Executive Committee and past Executive Committees over the years. I have learned immensely from our Past Presidents, whose leadership has elevated SSE, SL to its present high standing. I am committed to building upon this strong foundation and to taking the Society to even greater heights.

I look forward to working closely with the newly elected Executive Committee, whose support and dedication will be vital to the success of our initiatives. I am also confident that our Corporate Members will continue to stand with us as strong partners in advancing the objectives of the Society.

Together with the Executive Committee, I reaffirm our commitment to work tirelessly for the benefit of our membership, the engineering industry, and the nation. We will carefully review the valuable suggestions and advice received and explore practical ways to implement them during our tenure.

The Society of Structural Engineers, Sri Lanka was established to safeguard the interests of its members and to enhance their knowledge in the fields of Civil and Structural Engineering through diverse platforms. Promoting and advancing the science and practice of structural engineering; organizing seminars, lectures, symposiums, and technical discussions; maintaining libraries; and publishing technical papers and books are among the core objectives defined at its inception. As President, I am fully committed to striving for excellence and achieving these objectives during my term.

We also wish to emphasize our willingness to support national rebuilding efforts. In the aftermath of landslides and flooding caused by the Ditwa storm, the Society is fully prepared to offer its expert services, particularly in the areas of buildings, bridges, and infrastructure. We strongly believe that the engagement of professional bodies such as SSE, SL will significantly enhance the quality, safety, and sustainability of reconstruction projects.

Another critical area of focus is the export of consultancy services. Sri Lanka is home to highly capable and competent structural engineers, and we possess significant potential to offer our expertise to countries with expanding construction markets. While individual firms are making commendable efforts, meaningful progress in this area requires strong government support and policy-level facilitation. SSE, SL stands ready to contribute towards this national objective.

I look forward to your continued guidance, cooperation, and support as we work together towards a stronger Society and a brighter future for the structural engineering profession in Sri Lanka.

Thank you.

Eng. Anuruddha Edirisinghe
BSc Eng (Hons), CEng (SL), PG Dip. Struct. Engineering, MIE(SL), MSSE(SL)
President 2025/2026

Investigation on Base Shears and Shaft Stresses of Conical Type Elevated Water Towers under Seismic Loading

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Abstract

Elevated water towers play a critical role in water supply systems, which is an essential need of any community. Therefore, a failure of an elevated water tower at a critical location in a disaster like an earthquake can lead to major crisis. This study investigates the seismic performances of conical type elevated water towers, which are commonly used in local water supply networks with the recent findings relevant to local seismicity. Three selected existing conical water tower structures having capacities of 350 m³, 500 m³, and 1000 m³ were analyzed under both full and empty tank conditions in this regard. Seismic analysis of these structures was conducted using both Equivalent Static analysis (ESA) and Response Spectrum Analysis (RSA) as per Eurocode while considering fluid-structure interaction using the added mass approach under RSA. According to results of the analysis with Peak Ground Acceleration (PGA) of 0.1g, a noticeable increase in stresses in supporting shafts of each considered tower was reported highlighting seismic vulnerability of these structures. Further, considerable overestimation of base shears and stresses in critical regions were observed when towers were analyzed under ESA compared with RSA as Fluid- structure interaction would not able to be properly addressed under ESA.

Keyword: Conical type elevated water tower, Equivalent Static analysis, Response Spectrum Analysis, Fluid-structure interaction

1. Introduction

Elevated water towers are essential components in urban and rural water supply systems, designed to store water at a height sufficient to maintain pressure in distribution networks, thereby ensuring uninterrupted service. These towers are predominantly constructed using reinforced concrete, which offers advantages in cost, durability, and ease of construction. Their geometric and structural configurations significantly affect their performance and vulnerability, particularly under extreme loading conditions such as seismic events.

Common geometric shapes used for elevated water towers include circular, rectangular, Intze, spherical, domed bottom, and conical forms. Figure 1 shows the classification of elevated water towers. Among these, Intze and conical-shaped tanks are frequently preferred for storage capacities exceeding 200 m³ due to their structural efficiency and material economy. In terms of support systems, towers are typically constructed using multiple columns, load-bearing walls, or hollow circular shafts. In Sri Lanka, elevated tanks supported by single hollow circular shafts are a common structural typology, especially for conical tanks.

Figure 1: Classification of Elevated water towers

The structural integrity and stability of elevated water towers are of paramount importance, as failure of such infrastructure could have caused serious consequences. A structural failure of water tower during natural disasters like earthquakes or cyclones may result in significant economic loss, threat to human life in the vicinity, and disruption to the water supply system of the area.

Until recently, Sri Lanka was generally considered a region with minimal seismic risk. However, recent studies have revealed the potential seismic vulnerability of the country. As a result, Sri Lankan authorities are in the process of developing the national annexure for seismic analysis to accommodate seismic considerations, though official documents have not yet been published.

Several researchers have contributed to the understanding of Sri Lanka's seismicity. Senavirathna et al. (2020) [1] proposed a seismic zoning map based on peak ground acceleration (PGA) values, recommending a

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PGA of 0.1g for the western and southern coastal belts and 0.05g for the eastern region. Gamage and Venkatesh (2019) [2] also suggested a PGA of 0.1g a 50-year return period for entire country, while Lewangamage and Kulatunga (2015) [3] also supported a similar recommendation. These studies collectively underscore the need for seismic analysis and design of critical infrastructure, including elevated water towers, within the Sri Lankan context.

Globally, elevated water towers have exhibited significant vulnerability during past earthquakes. For example, Rai (2003) [4] and subsequent studies reported extensive failures of towers especially those with central hollow shafts during the 2001 Bhuj earthquake in India, attributing the collapses to lack of redundancy and insufficient design for seismic loads. Figure 2 illustrates a failed tower of this typology during Bhuj earthquake.

Figure 2: Water tower collapse during Bhuj earthquake in India (Rai (2003) [4])

Moreover, seismic performance is affected by several parameters, such as liquid sloshing, tank aspect ratio, and base fixity. Moslemi (2011) [5] emphasized the critical impact of these factors, while Patil and Talikoti (2015) [6] highlighted the significance of staging height and the need to employ spring-mass models to accurately capture fluid–structure interaction during seismic analysis.

Considering these vulnerabilities, it is imperative to investigate the seismic performance of elevated water towers especially those originally designed without consideration of seismic loading. This study therefore focuses on the seismic vulnerability assessment of conical-type elevated water towers with central hollow shafts, aiming to assess their behavior under seismic loads using analytical models calibrated with Sri Lankan field conditions.

2. Methodology

Three conical elevated water towers with storage capacities of 350 m³, 500 m³, and 1000 m³ were selected for this study as these commonly use capacities in water distribution networks. Dimensional data for each tower was obtained from actual design documents and schematics. Typical sectional elevations of these towers are shown in Figure 3.

The selected towers were modeled using SAP2000 finite element analysis software. The models were developed as three-dimensional shell element structures, considering axisymmetric geometry and divided into appropriate meshing zones. The structural elements were discretized to capture realistic deformation and stress distribution patterns under seismic loads. Table 1 presents the geometrical parameters of considered towers.

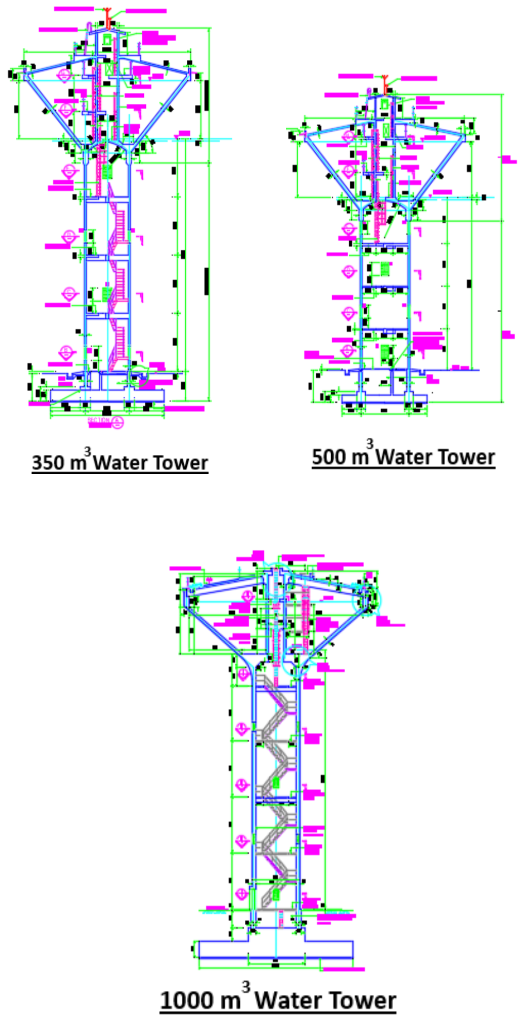


Figure 3: Sectional elevations of considered conical elevated towers

It was decided to use Response Spectrum analysis and Equivalent Static analysis to assess the seismic performances of these structures and to compare results of Response Spectrum analysis and Equivalent Static analysis. PGA value of 0.1g was selected for this analysis based on the already discussed literature of seismicity relevant to Sri Lanka. It was considered Soil type A which is rock or hard soil and the spectrum type is 2 (the magnitude is less than 5.5) for development of response spectrum and calculation of equivalent static forces with a damping of 5%. Figure 4 shows the Response Spectrum curve developed for this analysis based on EC 8 [7].

Table 1 - Dimensions of the water towers

Tank Components	$350m^3$	$500m^3$	$1000m^3$
Height of stagging system	20.0m	18.0m	30.0m
Height of the Tank	7.6m	8.5m	10.5m
Diameter of the cone (external)	14.6m	16.5m	21.5m
Diameter of internal dome(external)	2.2m	2.2m	2.0m
Diameter of stagging column(external)	4.2m	5.0m	6.0m
Diameter of foundation(external)	10.5m	8.9m	19.0

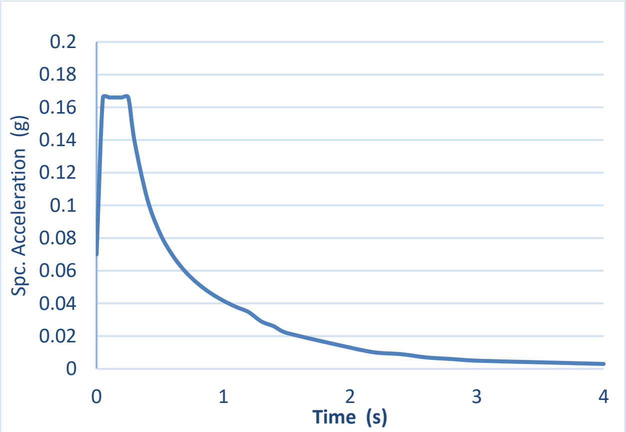
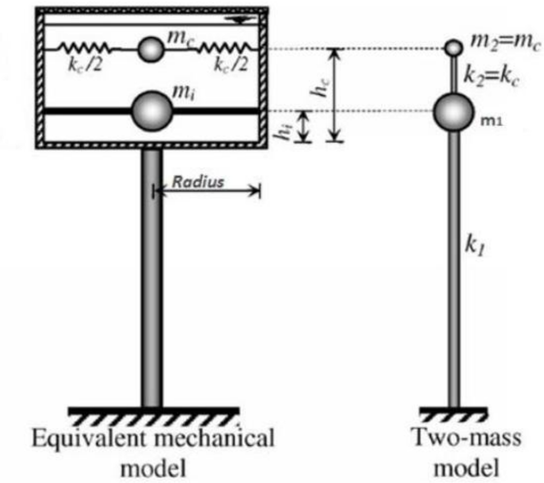


Figure 4 : Response spectrum curve considered for the analysis

Since wind loads are the predominant lateral loads that are considered for design of these types of structures, considered models were analyzed under a design wind speed of 33 m/s as well to compare responses of wind analysis with same of seismic analyses. Both tank empty condition and tank full conditions were separately considered in this analysis. In the tank full condition, it is required to consider mass of water volume and the interaction of water with the structure during the seismic analysis for accurate prediction of seismic responses. However, in case of equivalent static analysis, there is no provision to accommodate fluid structure interaction other than considering additional masses relevant to respective water volumes of structures during calculation of seismic forces. Hence, in equivalent static analyses, additional masses representing water volumes were considered at respective tanks levels and seismic forces were calculated accordingly. Then calculated forces were assigned to nodes of respective levels based on the directions of EC 8 [7] regarding the distribution of the base shear.

As per literature, when a tank filled with a liquid is subjected to a seismic force, bottom part of the liquid volume accelerates rigidly with tank walls, and the top part of the liquid volume behave independently causing sloshing effects on tank walls. The mass relevant to top part causing sloshing effect is called as convective mass (m_c) and remaining part of accelerate rigidly with tank walls is called as impulsive mass (m_i). Simplified mechanical analog has been developed by Housner (1963) [8] to model this phenomenon, and the conceptual model of this simplified analog has been presented in Figure 5.

Based on this fundamental theory, Egyptian seismic design code ECP201-2012 [9] has provided equations and graphs to calculate parameters (m_i,m_c, h_i,h_c and k_c) for conical shape tanks by considering equivalent cylindrical tank. This approach was used to calculate above parameters of each considered conical shape overhead tanks, and calculated sloshing parameters are presented in Table 2.



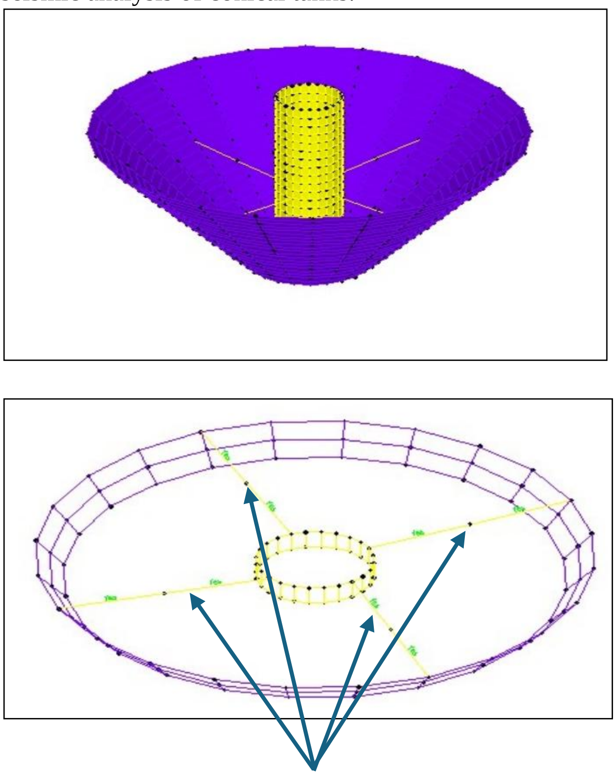
m_i = Impulsive mass of liquid + Container mass + Portion of supporting structure mass

Figure 5: Simplified mechanical analog to model sloshing effect

Table 2 : Calculated sloshing parameters for considered tanks

Parameters of Sloshing	350 m^3	500 m^3	1000 m^3
m_i (MT)	154	210	440
m_c (MT)	196	290	560
h_i (m)	2.05	2.4	3.04
h_c (m)	3.13	3.6	4.64
k_c (kN/m)	413	523	797

SAP2000 software was used to analyse tanks with added mass approach. As already discussed, in order to account for sloshing, convective masses (based on these calculated parameters for each case) were assigned at respective h_c levels with springs in main orthogonal directions. The typical way of assigning convective masses for these tanks is graphically presented in Figure 6. A similar approach has been used by Rashed et al (2019) [10] in their study on seismic analysis of conical tanks.



Masses with springs to represent convective masses

Figure 6 : Assignment of convective masses for tanks

According to the Housner's approach, regarding impulsive mass of water volumes which are moving with the tank wall, calculated additional masses were assigned to nodes of shell elements representing walls to represent impulsive masses. Material properties of Grade 35A concrete were assigned for shell elements. It was assumed pinned condition at the base level for all towers.
A typical overall analytical model developed in SAP 2000 for 350m^3 tower is presented in Figure 7.

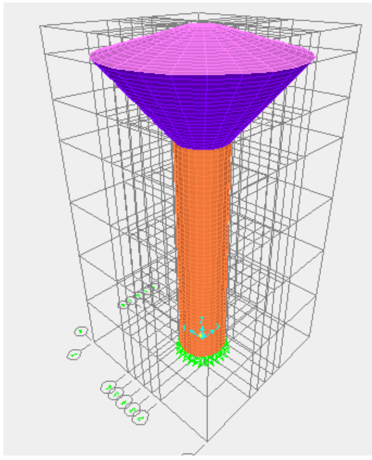


Figure 7 : SAP 2000 model developed for the 350m^3 tank

For studying seismic responses of considered structures with different analytical approaches and comparing the same with conventional wind analysis results.

Following load combinations were considered in this study. First four load combinations represent governing ultimate design load combinations of these types of structures as per BS8110:1990 without seismic loads. Last four cases represent worst case combinations under seismic loads as EC 8.

1. 1.4 G_K+ 1.6 Q_K (Without Water)
2. 1.4 G_K+ 1.6 Q_K (With Water)
3. 1.4W_K + 1.0 G_K (Without Water)
4. 1.4W_K +1.0 G_K (With Water)
5. 1.0EQ_{st} + 1.0 G_K (Without Water)
6. 1.0EQ_{st} + 1.0 G_K (With Water)
7. 1.0EQ_{RS}+ 1.0 G_K (Without Water)
8. 1.0EQ_{RS} + 1.0 G_K (With Water)

Where;
G_k – Dead load
Q_k- Imposed load
W_k – Wind load
EQ_{st} -Equivalent static seismic load
EQ_{RS}- Response Spectrum Seismic load

3. Result and Discussion

Reported Base shears of different tanks under equivalent static analysis and Response spectrum analysis extracted from SAP 2000 and are presented in Table 3. The same data in graphical forms are presented in Figure 8 and 9 separately.

Table 3: Reported base shears

Tank type	Tank empty condition		Tank full condition	
	Eq. static (kN)	Response Spectrum (kN)	Eq. static (kN)	Response Spectrum (kN)
350 m^3	200	217	404	264
500 m^3	312	326	697	436
1000 m^3	580	643	1200	730

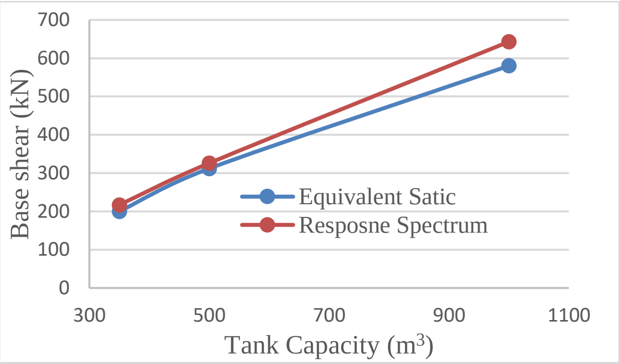


Figure 8 : Variation of Base shear under tank empty condition

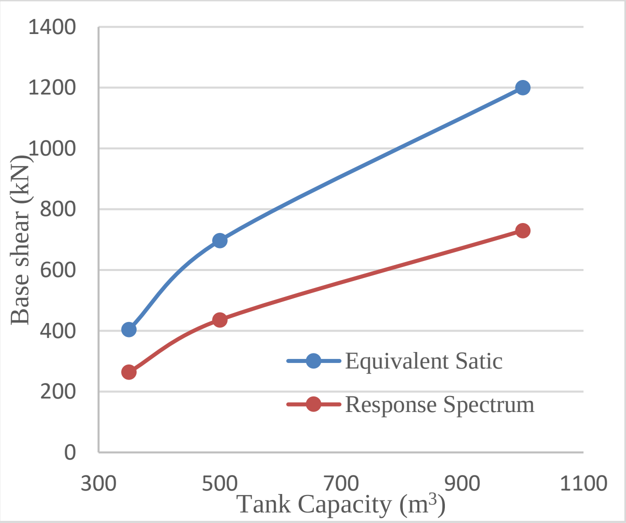


Figure 9 : Variation of Base shear under tank empty condition

As it can clearly observe in Figure 8, reported base shears from Equivalent static analysis and Response spectrum analysis are almost same under empty tank conditions. Dominancy of first mode of these structures under dynamic lateral loads with the behaviour as inverted pendulums would be probable reason for this observation (In EC 8 and many other seismic codes, base shears are calculated considering spectral acceleration of first modes and hence, even if other modes of structures are considered in Response spectrum analysis, almost equal base shears can be expected as for these type of structures as first mode is far dominant under dynamic lateral loads due to inverted pendulum like behaviour of these structures). However, reported base shears from Response spectrum analysis are slightly high in all considered cases.

Nevertheless, there is a considerable difference between base shears reported for equivalent static analyses and Response spectrum analyses of towers as it can observe in Figure 9. Base shears under equivalent static analysis are considerably high in all cases. The omission of consideration of sloshing effect of water during equivalent static analyses would be the main probable reason for this observation. In case of equivalent static analysis, it was assumed that both water and structures achieved the peak responses at the same time as mass of water and structure had been considered as one unit. However, in case of Response spectrum analysis, with the introduction of the springs between impulsive masses and tank's walls representing more realistic condition, peak responses two masses under dynamic loads would pick at different times. That would be the main probable reason for this observation. A similar type of observation had been reported by Madhurar and Madhuri (2013) [11] in their research on seismic performances of elevated water tanks under static and dynamic analytical approaches.

Since most of the tower failures have been taken place closer to bottom of staging columns, maximum stresses in walls in vertical directions under critical load combinations were studied and tabulated in Table 4.

Table 4: Maximum stresses in walls of tower shafts

Tank type / Load comb.	Tank Empty		Tank full	
	Max. Compress. Stress N/mm^2	Max. Tensile stress N/mm^2	Max. Compress. Stress N/mm^2	Max. Tensile stress N/mm^2
350 m^3				
$1.4\ G_k + 1.6Q_k$	2.61	-	3.59	-
$1.4\ w_k + 1.0G_k$	2.65	-	3.63	-
$1.0EQ_{st}+1.0G_K$	3.35	0.09	5.13	1.94
$1.0EQ_{RS} + 1.0G_K$	3.52	0.20	4.01	0.61
500 m^3				
$1.4\ G_k +1.6Q_k$	2.52	-	3.60	-
$1.4\ w_k +1.0G_k$	2.32	-	3.41	
$1.0\ EQ_{st} + 1.0\ G_K$	2.90	-	5.08	2.03
$1.0\ EQ_{RS} + 1.0\ G_K$	3.39	0.18	4.01	0.83
1000 m^3				
$1.4\ G_k +1.6Q_k$	2.26	-	3.14	-
$1.4\ w_k +1.0G_k$	2.14	-	2.99	-
$1.0\ EQ_{st} + 1.0\ G_K$	2.75	-	4.35	1.46
$1.0\ EQ_{RS} + 1.0\ G_K$	2.86	-	3.24	0.24

As it can clearly observe in Table 4, it has not reported any vertical tension in stagging columns under ultimate vertical load combination or under wind load combination in any of the towers. However, under seismic load combinations (especially under tank full conditions) vertical tensions have been reported in each tower. Understandably, reported tensile stresses are high under equivalent static analysis compared with stresses reported under Response spectrum analysis.

Reporting tensile stresses would become a serious concern as these staging columns would have been designed as columns under compressive stresses based on vertical and wind load analysis results. With development of vertical tension, the amount of reinforcements provided considering compression may become insufficient and it can cause severe cracking or collapsing of the tower. Further, a considerable increase in compressive stress in staging columns has been observed under seismic load cases in all considered towers. If the stagging column is having lack of confinement, the increment of compressive stress may lead to catastrophic failures. These would be the probable reasons for failures and severe cracking of stagging columns of elevated water tanks and breakages of reinforcements probably due to excessive tensile stresses are clearly visible in the collapsed water tower during 2001 Bhuj earthquake in Figure 10. In summary, according to stresses reported in staging columns of all considered towers in this analysis, there is high probability to occur failures or severe damages to these towers under expected seismic loads under local condition since tensile stresses and high compressive stresses (exceeding their original design stresses) have been reported during more accurate Response spectrum analyses.

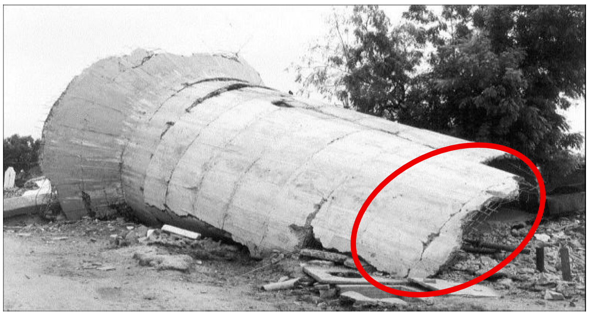


Figure 10: Damaged and collapsed towers during 2001 Bhuj earthquake

4. Conclusion

The main aim of this study is assessment of seismic performances of conical-type elevated water towers with different analytical approaches under applicable local seismic conditions and comparison of results while highlighting any structural concerns of these structures under seismic loads.

Based on results, Equivalent static analysis can not be recommended to model this type of towers escpecially with tank full condition as there is no effective way to model water- structure interaction in that method. Hence, base shears and stresses in staging columns could be considerably overestimated by using Equivalent static analysis as it was observed in this study.

However, staging columns of this type of towers may exceed design stresses (relevant to ultimate vertical loads and wind loads) under seismic loads applicable to Sri Lanka. Hence, Re-assessment of these types of towers which were not designed considering seismic loads is recommended to ensure structural integrity of these towers under probable seismic events relevant to local condition.

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Capacity Assessment of a Wire Rope Bridge in Deraniyagala, Sri Lanka

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Abstract

Wire rope bridges are one of the oldest bridge structures in the world and there are various types of wire rope bridges in the world. These bridges are popularly used for light to moderate traffic in rural and mountainous areas where construction cost of conventional bridge types is expensive. Sri Lanka has a few numbers of wire rope bridges and the Roocastle wire rope bridge which was constructed in 1938 and renovated in 2020, is an important bridge in Deraniyagala area. It is the only simple suspension type wire rope bridge used for vehicle traffic in Sri Lanka. This bridge runs over Seethawaka river and located in 10.4 km distance from Dehiovita town in Roocastle estate in Digala area. The length and width of the bridge are 41.5 m and 2.3 m, respectively. The deck is made of Hora timber plunks and supported by sixteen numbers of wire ropes of 26 mm in diameter. At present, heavy vehicles pass over the bridge and the main aim of the study is to assess the capacity of the wire rope bridge. Field visits and data collection were conducted, along with laboratory testing of timber and rope materials, hardness measurements of structural steel sections which was used to fix wire ropes at two ends. After data collection, CSIBridge v.22 software was used to develop numerical model and assess load capacities of wire ropes and timber deck. According to the obtained results from CSIBridge numerical model and calculations, it can allow to use vehicles on Roocastle bridge which are below 200 kN without any failure of wire ropes and timber deck, whereas heavy vehicles exceeding 200 kN should not be accommodated to the bridge. This study illustrates the usefulness of wire rope bridges for Sri Lanka in carrying vehicular transportation.

Keywords: *Wire rope, Timber deck, Load capacity, Yield strength*

1. Introduction

Wire rope bridges are well-known structures in the modern world and there are various types of wire rope bridges in the world. These bridges are popularly used for light to moderate traffic in rural and mountainous areas where construction cost of conventional bridge types is expensive. There are a few wire rope type bridges [4] in Sri Lanka but there is only one wire rope bridge used for vehicle moving. The selected vehicle moving wire rope bridge runs over Seethawaka river, located in 10.4 km distance from Dehiovita town in Roocastle estate in Digala area. It is considered to be built by the British in 1938. The length of this bridge is 41.5 m and the width is 2.3 m and main structure prepared by wire ropes and timber deck as shown in Figure 1.

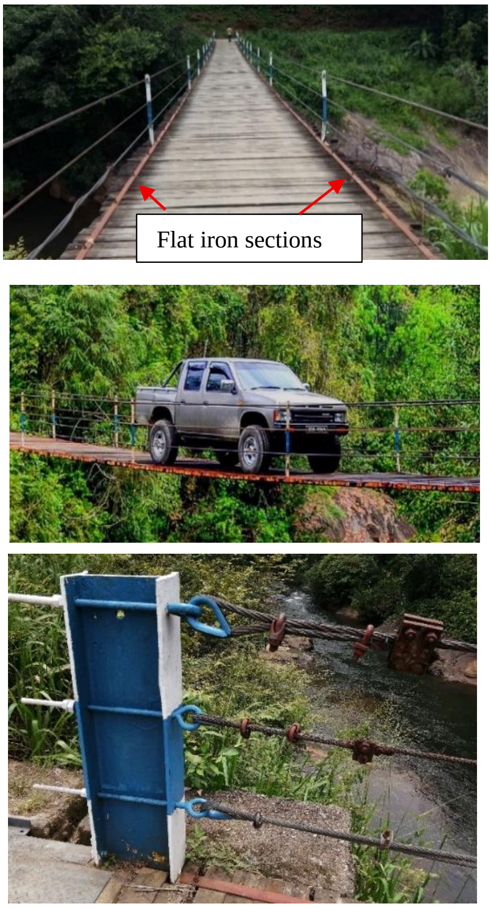

Figure 1: Few views of the bridge and its support

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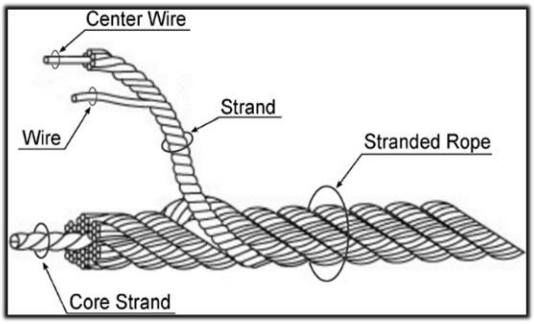
Imposed load of the moving vehicles is carried by sixteen numbers of wire ropes with 26 mm diameter and they are connected to oval eye bolts in a horizontal H-iron structure of embankment using wire rope ferrule and thimble [5]. Horizontal H-iron is then supported to two vertical H-iron structures through bolting. There is no welding at these connections.

Deck was prepared by 100 mm*50 mm 'Hora' timber sections and 1050 mm height handrails prepared by 26 mm diameter one wire rope and 18 mm diameter two wire ropes, these wire ropes go through 50 mm*6 mm flat iron plates and they are connected to oval eye bolts in a vertical H-iron structure of embankment using wire rope ferrule and thimble as shown in Figure 1. The individual movement of the timber planks due to vehicle loading is restricted by the 6 mm *100 mm flat iron sections fixed at the either side of timber planks and two flat iron sections are bolted to the timber planks as shown in Figure 1(a).

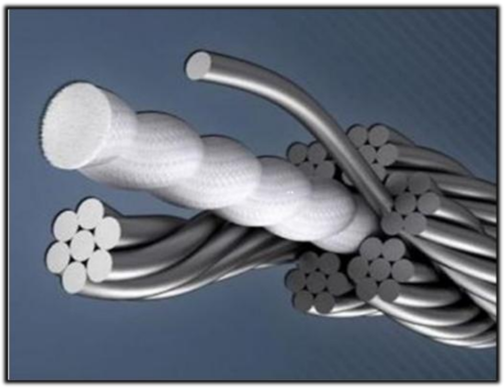
Roocastle wire rope bridge is generally used for pedestrian and vehicles, and its main purpose is to transport rubber latex. It was renovated by the estate company and funded by Fair Rubber Association in Germany. The bridge was renovated and handed over to the beneficiaries on 18th December in 2020.

2. Structural Characteristics of Wire Ropes

The term cable is often used interchangeably with wire rope. However, in general, wire rope refers to the cables with diameters larger than 3/8 inch. Sizes smaller than 3/8 inch are designated as cable or cords. Two or more wires concentrically laid around a center wire is called a strand. It may consist of one or more layers. Typically, the number of wires in a strand is 7, 19, 24 or 37. In terms of product designation, 6 strands with 19 wires in each strand and center core would be a 6×19+FC cable. 6 strands with 7 wires in each strand and center core would be a 6×7+FC cable as shown in Figure 2 [7]. 6 strands with 24 wires in each strand and center core would be a 6×24+FC cable. In general, center wire is prepared by fiber materials.



(a)



(b)

Figure 2: Details of wire rope; (a) components, (b) 3D view

Initially wrought iron wires had been used, but today steel is the main material used for wire ropes. [6].

2.1 Wire Rope Strength

Wire rope in service is subjected to several kinds of stresses. The stresses most frequently encountered are direct tension, stress due to acceleration, stress due to sudden or shock loads, stress due to bending, and stress resulting from several forces acting at one time. For the most part, these stresses can be converted into terms of simple tension, and a rope of approximately the correct strength requirement can be selected. As the strength of a wire rope is determined by its size, grade and construction, these three factors should be considered.

Wire rope strength is usually measured in tons of 2,000 lbs (906 kN). In published material, wire rope strength is shown as minimum breaking force (MBF) or nominal strength. These refer to calculated strength figures that have been accepted by the wire rope industry. When placed under tension on a test device, a new rope should break at a value equal to, or higher than the minimum breaking force shown for that rope.

2.2 Tensile Strength Grade of Wire Ropes

Wire tensile grade is a level of requirement of tensile strength of a wire and its corresponding range. It is designated by the value according to the lower limit of tensile strength and is used when specifying wire and when determining the calculated minimum aggregate breaking force. Common tensile strength grades are 1570 N/mm^2, 1670 N/mm^2, 1770 N/mm^2, 1870 N/mm^2 and 1960 N/mm^2. Details of wire ropes in Roocastle bridge are given in following section.

3. Geometric Details of the Bridge

A 3D view of the bridge is shown in Figure 3 and geometric details are tabulated in Table 1.

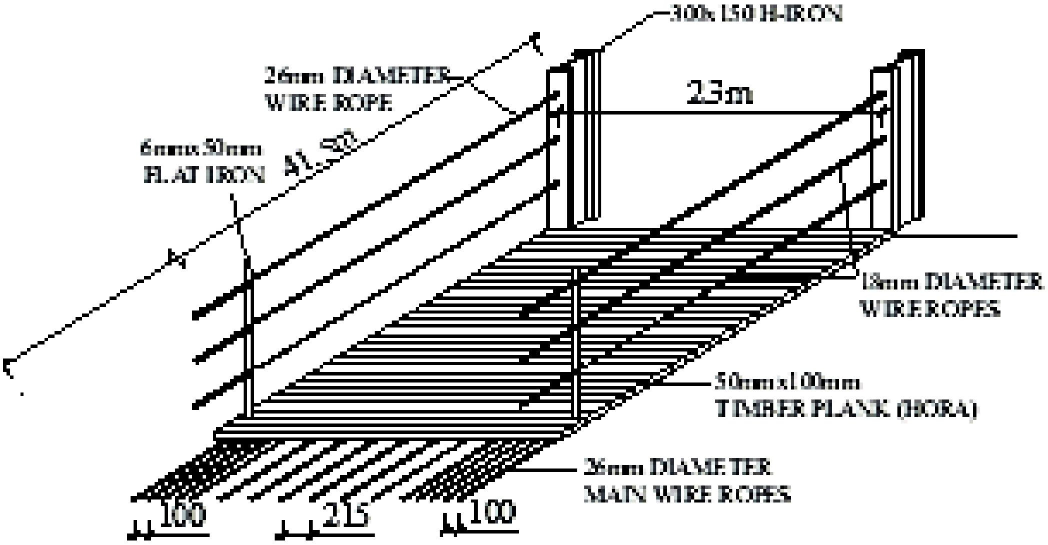


Figure 3: Schematic view of the wire rope bridge

Table 1: Details of Digala Roocastle bridge

<table>
<tr><th></th><th>Description</th><th colspan="4">Measurements</th></tr>
<tr><td>1</td><td>Length of bridge</td><td colspan="4">41.5m</td></tr>
<tr><td>2</td><td>Width of the bridge</td><td colspan="4">2.3m</td></tr>
<tr><td>3</td><td>Diameter of main wire ropes</td><td colspan="4">26mm</td></tr>
<tr><td>4</td><td>Number of main wire ropes</td><td colspan="4">16 Nos</td></tr>
<tr><td>5</td><td>Gap between main wire ropes</td><td colspan="4">100mm for five wires in both edges
215mm for six wires in middle.</td></tr>
<tr><td rowspan="2">6</td><td rowspan="2">Timber piece detail of deck.</td><td>Length</td><td>Width</td><td>Height</td><td>Type</td></tr>
<tr><td>2.5m</td><td>100mm</td><td>50mm</td><td>Hora</td></tr>
<tr><td rowspan="2">7</td><td rowspan="2">Details of H-Iron</td><td>Height</td><td>Length</td><td colspan="2">Width</td></tr>
<tr><td>1050mm</td><td>300mm</td><td colspan="2">150mm</td></tr>
<tr><td rowspan="2">8</td><td rowspan="2">Details of handrail wire ropes</td><td colspan="4">24mm Diameter top wire both side</td></tr>
<tr><td colspan="4">18mm Diameter two bottom wires both side</td></tr>
<tr><td>9</td><td>Detail of handrail flat iron</td><td colspan="4">1m height, 50mmx6mm flat iron</td></tr>
</table>

4. Types of Wire Ropes of the Roocastle Bridge

4.1 Main Structural Wire Rope

Main structural wire rope of the bridge is 26 mm diameter wire rope. It is consisting of six number of steel strands and one number of fiber core strand24 wires and one fiber core in single steel strand is shown in figure 4.

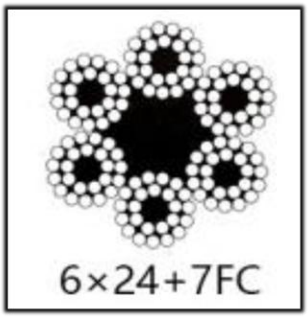


Figure 4: Cross section and image of main wire ropes

4.2 Top Wire Rope of the Handrail

Top wire rope of handrail of Roocastle wire rope bridge is 26 mm diameter wire rope. It is consisting of six number of steel strands and one number of fiber core strand. The 7 wires in single steel strand is shown in Figure 5.

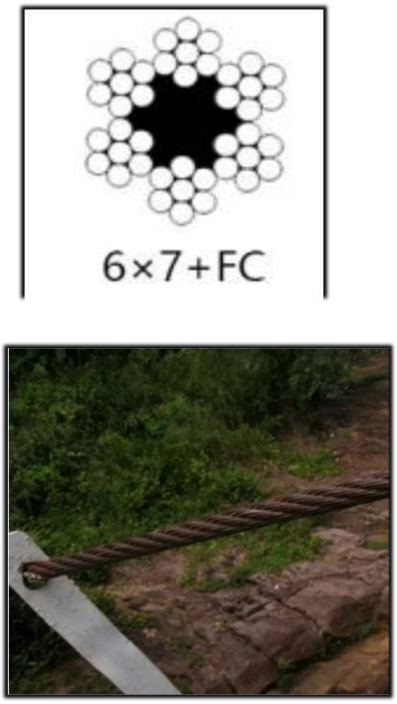


Figure 5: Cross section and image of top wire rope of the handrail

4.3 Middle and Bottom Wire Ropes of the Handrail

Middle and bottom handrail wire ropes of the bridge are 18 mm diameter. It is consisting of six number of steel strands and one number of fiber core strand. The 19 wires in single steel strand as shown in Figure 6.

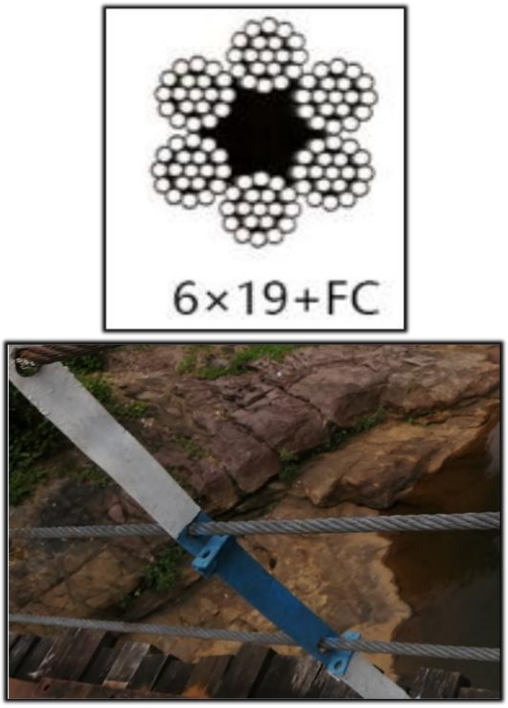


Figure 6: Cross section and image of middle and bottom wire ropes of the handrail

5. Properties of Hora timber

Hora timber is a class 1 timber as per State Timber Corporation in Sri Lanka. Botanical name of Hora timber is ‘Dipterocarpus zeylanicus’ and it includes in the family of ‘Dipterocarpaceae’. Some main properties of Hora timber shown table 2 [1].
Timber durability is classified as non-durable (<5 years), moderately durable (5-10 years) and durable (>10 years). ‘Hora’ timber is generally considered as moderately durable.

Table 2: Main Mechanical Properties of Hora Timber

Name of Timber	Density class	Density At 12% moisture content (kgm^{-3})	Modulus of elasticity (Nmm^{-2})	Modulus of rupture (Nmm^{-2})	Compression parallel to grain (Nmm^{-2})
Dipterocarpus zeylanicus (Hora)	High Density	762	12,142	92	47

6. Material Testing of Components

6.1 Tensile Testing for Main Wire Rope

Piece of wire rope which removed bridge renovation project in 2020, was obtained and tested for breaking force of the cable through tensile testing facility at the Civil Engineering laboratory of Open University of Sri Lanka in Nawala. The sample collected is shown in Figure 7.

Length of the collected wire rope sample was 610 mm, diameter of the sample was 26 mm, weight of the sample was 1230 g. Sample wire rope was consisting of 6 strands and main fiber center core. Each strand was consisting 24 wires and fiber center core. Therefore, the sample is 6x24+7FC.

Figure 7: Collected sample of main wire rope

Universal tensile test machine (UTM) was used in tensile testing of rope material and compressive strength measurements of timber material. Figure 8 shows the testing machine.

Figure 8: Tensile testing using universal test machine in the laboratory

6.2 Test Procedure of Wire Sample

i) Suitable two jaws are selected and placed in universal test machine.
ii) The wire rope sample is placed between the two jaws and clamped firmly.
iii) Entered the data to computerized system.
iv) The electricity supply is given to the universal test machine.
v) The jaws are pulled apart to apply tension on the sample.
vi) The tension is increased until the sample reaches the fracture point.
vii) Observed all results through the computer. Computerized system created a graph versus applied load and position.
viii) Also collected the all result through computerized system.

6.3 Final Result of the Tensile Testing

After breaking the wire rope sample, a data table and graph (Graph of position (mm) versus load (kN)) were obtained through the computerized system. Computerized system increases the accuracy of the test result to avoid human errors by data readings. Figure 9 shows the broken wire rope sample and table 3 shows the test results of wire rope sample.

Figure 9: A view of the broken wire rope

As per the received graph and result table from tensile test, the breaking force of the sample wire rope is 267.2 kN. As per manufacture's specifications, breaking force of the sample wire rope is 278 kN. Then, it can be observed a 4% reduction of the breaking force of the wire rope.

Table 3: Experimental test summary of wire rope

Name	The Value	Unit
Diameter of specimen	26	mm
Original gauge length	308	mm
Proof prolongation, total extension	0.5	mm
Proof prolongation, non-proportional extension	0.2	mm
Maximum force	**267.20**	kN
Tensile strength*	503.26	MPa
Lower yield load	231.83	kN
Lower yield strength*	436.66	MPa
Upper yield load	231.84	kN
Upper yield strength*	436.66	MPa

*strengths are calculated considering nominal diameter of the rope specimen (26mm)

6.4 Bending Test on Wooden Beam using Universal Testing Machine

One and half year-old piece of Hora timber was used to find out to timber properties. Bending test [2 &3] was done using UTM at the Civil Engineering Laboratory of Open University of Sri Lanka in Nawala. Images of timber sample and bending test are shown below.

Figure 10: Bending test on Hora timber sample

6.5 Detail of the Timber Sample

Type of the collected timber sample was 'Hora' and scientific name of the Hora timber is 'Dipterocarpus zeylanicus'. Length of the collected timber sample was 508 mm, width of the sample was 100 mm, depth of the sample was 50 mm and weight of the sample is 1853 g.

6.6 Test Procedure of Timber Specimen

i) Steel reaction block was placed on the UTM symmetricaly.
ii) The timber sample was placed symmetrically on the steel reaction block.
iii) Steel rod was placed on the center of timber sample to apply point load on the timber sample.
iv) The load was applied on the timber sample and increase the load gradually up to breaking the sample.
v) Results were observed and collect from computerized system.

6.7 Test Results of Timber Specimen

After breaking the timber sample, observed a crack bottom side of the timber sample as shown in Figure 11. Maximum load as per the test result is 22.81 N and maximum deflection when timber sample breaking is 6.468 mm.

Figure 11: Hora timber sample and bottom cracks after bending test

6.7 Ultimate Tensile Strength Measurements of Steel Columns using Brinell hardness

Brinell hardness measurements were performed on steel abutment columns and then converted to ultimate tensile strength at six locations. It was found that ultimate tensile strength of steel abutments is in the range of 460 MPa to 480 MPa.

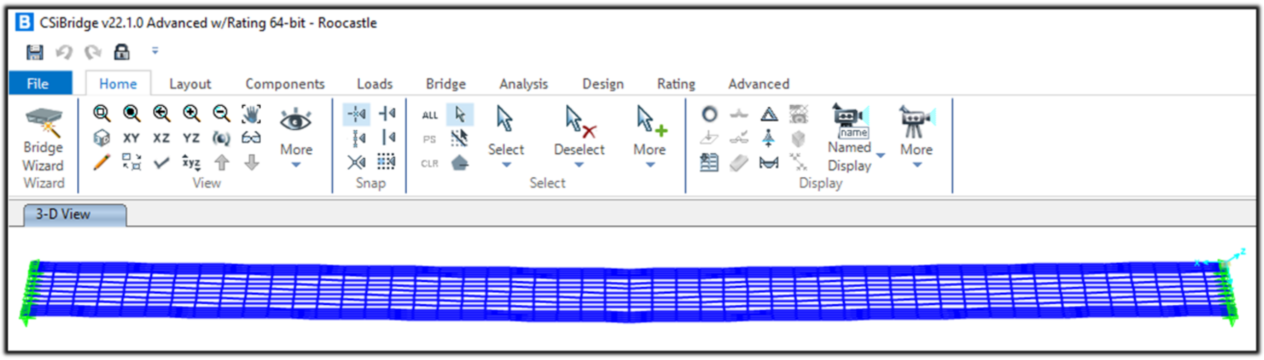


Figure 12: Numerical model of the bridge

7. Numerical Modelling of the Bridge

CSI Bridge software was used to assess maximum capacity of wire ropes and timber deck due to live loads on bridge. Modeling, analysis and design of bridge structures have been integrated into CSiBridge to create the ultimate in computerized engineering tools. It is the most versatile and productive software program available for the analysis and design of bridges.
As the side ropes are mainly connected to provide the railing function and the contribution for the load transfer by them is small, side cables can be structurally neglected. The 16 number of ropes and the timber deck were modelled. In built cable properties are used to model the bridge. 1000mm x 50mm idealized cross timber planks are placed on the wire ropes. End nodes of the bridge were hinged supported as there are not any bending moment at the cable end to the support beam. Created numerical model using CSI bridge is shown in Figure 12. Figure indicated 16 numbers wire ropes and 50 numbers idealized timber planks. Loads and load combinations were defined according to Euro codes. Following two loads were defined.

a. Self-weight of cables
   Self-weight of the cables and timber planks shall be automatically calculated by the general material details of the software.
b. Traffic loads
   Traffic actions mentioned in the Eurocode can be considered for the analysis of the bridge. As per Eurocode uniform traffic load should 2.5 kN/m^2.

Four load models according to BS EN 1991-2:2003 [8] were defined as shown below.

LM1
Uniform traffic load of 2.5 kN/m^2 and an axel load of 200 kN is applied includes dynamic amplifications. Then total load is 400 kN from both axels.
LM2
Under LM2 loading, a single axle load of 400 kN is considered with dynamic amplifications. In here consider only rear axle load because front axle load is very low in some heavy vehicles.
LM3
Since the bridge is 2.3m wide and no heavy unusual trucks are allowed, LM3 loading with unusual multi axle truck loads shall be neglected.
LM4
A uniformly distributed 5 kN/m^2 crowd loading is considered. As per Eurocode 1 this 5kN/m^2 includes dynamic amplifications due to foot loadings too. Therefore, by applying uniformly distributed load of 5kN/m^2, No additional dynamic load is needed to apply. Since 2.5 kN/m^2 traffic load previously added, LM4 loading was considered as 2 times traffic load.

Following combinations mentioned in the Eurocode 1 were considered as follows.
EC1 CMB 1 :1.35 Dead Load + 1.5 LM1
EC1 CMB 2 :1.35 Dead Load + 1.5 LM2
EC1 CMB 3 :1.35 Dead Load + 1.5 LM4

However, consideration of above combinations mentioned in Eurocode 1 noted to be somewhat overconservative for this type of bridge. Therefore, following combination were also considered for sensitivity analysis under the truck load.

SNS CMB 1 :1.35Dead + 1.5xAxle load from LM1
SNS CMB2 :1.35Dead + 1.5 x 0.5x Axle load from LM1 (Vehicle with 100kN Axle Load)

Table 4: Results of the numerical model analysis

Combination	Cable loads (kN) middle to edge	Cable Tensile capacity (kN)	Deflection (mm)	Comments
EC1 CMB1	123.19 to 414.65	200.25	72	12 cables (6 cables from each end fails)
EC2 CMB2	61.03 to 258.31	200.25	57	8 cables (4 cables from each end fails)
EC3 CMB3	11.36 to 98.46	200.25	35	Cables safe
SNS CMB1	20.71 to 225.64	200.25	53	2 cables (1 cable from each end fails)
SNS CMB2	12.37 to 170.55	200.25	46	Cables Safe

7.2 Observation of Wire Rope Capacity

Since the single truck with an axial load 200 kN (Total load is 400 kN) makes failure of the cables (As per SNS CMB1), larger trucks cannot be accommodated in the bridge. As SNS CMB 2 Combination reported that cables are safe, trucks with an axle load of 100 kN do not cause any cable failure. Therefore, vehicle below 100 kN would possible to be drived on Roocastle wire rope bridge safely.

Further, the bridge is safe enough to with stand the maximum pedestrian load of 5 kN/m^2 with the vibration amplifications. Latex bowser total load is 41.79 kN and sand dump truck total load is 85.35 kN respectively. Hence, both of these values are lower than SNS CMB2 value and therefore bridge would be safe with bowser load and dump truck load.

7.3 Assessment of timber planks

Due to load combination value of wire rope, SNS CMB 2 combination satisfies the wire rope capacity of the bridge. Then, such load should checked with the structural capacity of timber planks.

0.5×LM1 value considered in SNS CMB 2 combination.

Then axel load is = 200×0.5
= 100 kN

Then tire load in one location is = 100/2
= 50 kN

Width of tire is = 0.2 m

Then UDL on timber deck is = 50/0.2
= 250 kN/m

Timber planks were modeled using CSIBridge software and flexural and shear stresses were checked against respective capacities and it was found that the section is structurally safe against shear and flexural failures.

8. Discussion and Conclusions

This study focused mainly on maximum capacity of wire ropes and timber deck due to vehicle moving of the Roocastle wire rope bridge. To accomplish above objective, CSIBridge model was prepared. Literature review, field visit and data collection of bridge, field testing and laboratory testing were performed. As per the received results through CSIBridge model, allowable vehicle load value is 200 kN. The main purpose of the Roocastle wire rope bridge is to transport rubber latex bowser, which weighs 41.79 kN and hence, it can cross the bridge without any wire rope failure. Similarly, it is observed that the small sand dump truck with 85.35 kN (1 Cube) is also able to be driven through the bridge without any issue. However, heavy vehicles such as large dump trucks, buses, and containers weighing more than 200 kN, exceed the bridge's capacity. Also, it is not recommended that two or more number of vehicles entering the bridge in simultaneously.

The Hora (Dipterocarpus zeylanicus) timber has been used for the Roocastle bridge deck, and it's bending strength is 41.13 N/mm^2 as per laboratory test results. Considering the safety of timber planks, the bending strength of Hora timber sample and bending stress of the timber deck due to vehicle movement were compared. The maximum bending stress of the timber deck is 27.16 N/mm^2 as per the CSIBridge model with 200 kN vehicle. As per the results, bending strength value is higher than the bending stress of the timber deck due to vehicle load, hence it would able to bear 200 kN vehicle load without any timber deck failure. Considering these results, it can recommend to drive vehicles weighing less than 200 kN, such as rubber latex bowser, small dump trucks, ambulances, cars, three wheels, vans, etc., through the Roocastle wire rope bridge without causing any wire rope or timber deck failure.

The sub surface support details at two ends were not available to authors and therefore, no analysis was done to assess foundations at two ends. However, authors recommend to do a proper foundation analysis in future.

9. Acknowledgment

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