Doctoral School of Geosciences

SCALE FORMATION AND TREATMENT PLAN IN INDONESIAN GEOTHERMAL WELLS

Theses of the Doctoral Dissertation

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Theses Booklet

I. Introduction and Aims of the Study

Geothermal energy represents a critical component in the global renewable energy portfolio, offering baseload power generation with minimal environmental impact compared to conventional fossil fuels. As documented by Gutiérrez-Negrín (2024), global installed capacity has demonstrated consistent growth, reaching approximately 16.3 GW by 2023, an almost eightfold increase from the 2,110 MW recorded in 1980 (Gutiérrez-Negrín, 2024). Despite this growth trajectory, operational challenges—particularly scale formation—continue to constrain the full utilization of geothermal resources worldwide, impacting both the technical performance and economic viability of geothermal projects.

Scale formation—the precipitation of minerals within wells, pipelines, and equipment—occurs when dissolved minerals exceed saturation limits due to changes in pressure, temperature, and chemical composition as fluids move from reservoir to surface conditions. This phenomenon substantially reduces operational efficiency through multiple mechanisms: diminishing wellbore diameter and flow capacity, decreasing heat transfer efficiency, and necessitating costly interventions. As Zarrouk et al. (2014) documented, scaling in geothermal heat exchangers can significantly reduce heat transfer efficiency, with even thin-scale layers creating substantial performance degradation. Operational costs escalate through higher energy consumption for pumping, increased chemical treatment expenses, and more frequent mechanical cleaning operations (Gutiérrez-Negrín, 2024).

The Indonesian archipelago, situated within the Pacific Ring of Fire at the convergence of three major tectonic plates, possesses approximately 40% of the world's geothermal potential with an estimated resource capacity of 28.5 GW distributed across 331 identified locations (Mohammadzadeh Bina et al., 2018). Despite this extraordinary endowment, Indonesia has developed only about 2.1 GW as of 2023, representing a utilization rate below 8% of the identified potential (ESDM, 2023). This substantial development gap stems from multiple factors, including regulatory challenges, financing constraints, and critically—persistent operational issues related to scale management

This research focuses specifically on three geologically and operationally distinct Indonesian geothermal fields that collectively represent the diversity of geothermal systems in the country: Patuha, Salak, and Kamojang. According to Sofyan et al. (2025), Kamojang manifests as a vapor-dominated system, while Sofyan et al. (2024) characterize Salak as primarily liquid-dominated with two-phase fluid (Sofyan et al., 2024). Rahayudin et al. (2020) classify Patuha as a vapor-dominated hydrothermal system with acid sulfate waters, stating that "volcano-hosted, vapor-dominated geothermal systems have great potential for power generation, although to date, such systems discovered globally remain limited in number (Rahayudin et al., 2020)."

The investigation centers on Well "X" in each field, providing detailed case studies that illuminate scale formation processes under different thermodynamic and chemical conditions. In Patuha, Well "X" exemplifies a steam-dominated well with 98% dryness, where analysis confirmed the presence of calcite scaling despite conditions traditionally considered resistant to such deposition (Sofyan, 2023). In Salak, Well "X" represents a water-dominated well with two-phase fluid, experiencing amorphous silica scaling, particularly at the transition between the

7" perforated liner and 13⅜" production casing (Sofyan et al., 2024). In Kamojang, Well "X" represents a vapor-dominated system where silica (quartz) and magnetite (Fe_3O_4) scales were identified at 900.74 m depth within the 13⅜" production casing (Sofyan et al., 2025).

Through systematic analysis of these three distinct geothermal environments, this research establishes correlations between fluid flow patterns, scaling mechanisms, and effective treatment planning methodologies. While liquid-dominated systems have received extensive research attention regarding scale formation, vapor-dominated systems, despite their significant presence in Indonesia's geothermal landscape, have been comparatively neglected in scaling studies. This research addresses this gap by comprehensively investigating scaling across both system types, thereby enhancing understanding of the complex interplay between thermodynamic conditions, fluid chemistry, and scale precipitation mechanisms.

The research specifically addresses several critical knowledge gaps: (1) the relationship between fluid flow regimes and scale formation locations across different system types; (2) the mechanisms of calcite scaling in high-dryness vapor-dominated systems previously thought to be less susceptible to such scaling (3) the influence of wellbore geometry transitions on localized scale formation; (4) the economic optimization of scale treatment methodologies for specific field conditions; and (5) the development of an integrated assessment framework that combines hydrodynamic, thermodynamic, and geochemical parameters to improve predictive capabilities for scale management.

Flow pattern characterization was conducted using the Hewitt-Robert method and WellSim software simulations, which revealed annular flow patterns coinciding with scale formation zones. Pressure-Temperature-Spinner (PTS) surveys provided critical field data for identifying flashing zones, such as at 1458.27 m depth in Patuha and 4600 ft depth in Salak, where pressure reductions triggered mineral precipitation. The geochemical analysis included PHREEQC simulation, Calcite Saturation Index (CSI) calculations and X-ray Diffraction (XRD) analysis of scale samples, enabling precise mineral identification and formation mechanism assessment.

The primary objectives of this dissertation are:

1. To investigate the mechanisms of scale formation across different geothermal reservoir types (vapor-dominated and water-dominated) by analyzing flow patterns, fluid dynamics, and geochemical conditions in the Patuha, Salak, and Kamojang fields.
2. To develop an integrated methodological framework for accurate identification and characterization of scale formation zones, utilizing flow pattern classification, Pressure-Temperature-Spinner (PTS) data, well integrity testing, and geochemical analysis.
3. To evaluate and compare scaling compositions—including calcite, amorphous silica, and silica-magnetite—across diverse geothermal environments and understand the influence of fluid properties, pressure-temperature gradients, and well architecture.
4. To formulate a cost-effective and field-applicable treatment strategy by, focusing on the broaching method in vapor-dominated systems, including

detailed tool specification, operational procedures, and economic feasibility analysis.

The findings from this research have yielded several significant scientific results, including: (1) the direct relationship between annular flow regimes and scale formation across all geothermal system types; (2) evidence that vapor-dominated systems with high dryness experience significant calcite scaling through CO_2 degassing mechanisms; (3) quantification of how wellbore geometry transitions influence scale formation; and (4) development of a broaching method treatment protocol for vapor-dominated systems that demonstrates a 93-96% cost reduction (USD 42,690 versus USD 628,147-1,195,339 for conventional methods) with projected payback periods of 3.3 months versus 4-10 years (Sofyan et al., 2025).

By addressing these objectives, this dissertation will improve both theoretical understanding and practical management strategies for addressing one of the most significant operational challenges in geothermal energy production, potentially unlocking a greater portion of Indonesia's vast geothermal potential and contributing to global renewable energy goals.

II. Applied Methods

This research employed a multi-methodological approach that integrated field data analysis, laboratory testing, computational modeling, and economic assessment to comprehensively investigate scaling phenomena across different Indonesian geothermal environments. The methodology was structured to facilitate systematic comparison between the three study sites—Patuha, Salak, and Kamojang—while accommodating their distinctive characteristics as vapor-dominated, water-dominated, and vapor-dominated systems, respectively.

Flow pattern characterization was conducted using the Hewitt-Robert method, which calculates flow pattern coordinates based on dimensionless parameters derived from field measurements. According to Sofyan, Wiharti, et al. (2023a), this approach required "determining the cross-sectional area of the flow pipe in the well X" followed by "determination of the coordinates of the flow pattern map" through specific equations considering dryness, mass flow, and fluid densities. The resulting coordinates were plotted on logarithmic graphs to identify specific flow regimes, with the research finding that "the flow pattern formed along the casing series of the well 'X' starting from the casing slotted liner 10" to the surface is an annular type flow pattern" (Sofyan, Wiharti, et al., 2023a). This analysis was complemented by WellSim software simulations, which incorporated site-specific thermodynamic properties to model fluid behavior under various operational conditions, providing validation that enhanced confidence in flow regime classifications.

Pressure-Temperature-Spinner (PTS) surveys provided critical field data for model validation and identification of flashing zones. In Patuha, these surveys revealed that "the flashing zone is at a depth of about 1458.27 m, because at that depth there is a decrease in pressure from 135 bara to 44 bara due to a change in diameter" (Sofyan, 2023). Similarly, at Salak, PTS data showed "a sudden change in pressure and temperature at depths of 4600 ft to 4800 ft" with "a pressure drop from 418.5 psig to 416.5 psig" (Sofyan et al., 2024). This precise localization of phase transitions allowed for targeted investigation of the scale formation zones and correlation with geological and engineering parameters.

Geochemical characterization comprised multiple analytical techniques tailored to the specific scale types encountered. For carbonate scales in Patuha, Calcite Saturation Index (CSI) calculations were performed using the formula "CSI = log(IAP/Ksp)" (Sofyan et al., 2024), yielding a value of 2.54 that definitively indicated calcite scaling potential. Silica scaling potential was assessed through the Silica Saturation Index, calculated as "SSI = (731/(4.52 - log SiO_2)) - 273.15" (Sofyan, 2023). In Kamojang, X-ray Diffraction (XRD) analysis of scale samples employed "a Rigaku MiniFlex II (Cu Kα radiation, λ = 1.5418 Å, operating at 30 kV and 15 mA)" with patterns analyzed "using Jade® 9.0 software and the Crystallography Open Database" (Sofyan et al., 2025). This comprehensive approach enabled precise mineral identification and formation mechanism assessment across different geothermal environments.

Well integrity testing incorporated multiple diagnostic methods to precisely locate scale deposits. In Kamojang, go-devil operations employed "a 203.2 mm (8 inches) go-devil tool" followed by "a 63.5 mm (2.5 inches) sinker" to map scale distribution through mechanical interaction (Sofyan et al., 2025). Physical samples were collected using specialized sample catchers, with Kamojang operations employing "a 139.7 mm (5.5 inches) sample catcher" and "an 88.9 mm (3.5 inches) sample catcher" to target specific depths (Sofyan et al., 2025). In Salak, the impression block technique identified scaling through distinctive surface markings, with tools becoming "stuck in the depth of 2,630-4,734 ft MD with a white stamp trace" (Sofyan et al., 2024). These complementary approaches provided robust documentation of scale locations and physical characteristics.

For the comprehensive treatment planning methodology developed for the Kamojang field, a systematic economic assessment framework was implemented. This included comparative cost analysis between treatment options: "drilling equipment (US$ 1,195,339), coiled tubing hole cleaning (US$ 866,181), bull heading (US$ 628,147), and broaching (US$ 42,690)" (Sofyan et al., 2025). The broaching method was subjected to detailed cost breakdown analysis incorporating direct costs ("broaching tools ($5,000), slickline unit mobilization ($15,000), labor ($8,000), fluid circulation ($2,000)") and indirect costs ("well downtime ($12,690)") (Sofyan et al., 2025). Revenue projections were calculated considering "a plant availability factor of 35%" and "steam price: USD 18.40/ton" (Sofyan et al., 2025), enabling accurate payback period determination under field-specific operational parameters.

III. New Scientific Results

Through the integration of field investigations, laboratory analyses, and computational modeling, this dissertation has yielded several significant scientific findings that advance both theoretical understanding and practical management of geothermal scaling:

T1: Hydrodynamic Flow Regimes and Scale Formation Correlation with Methodological Validation

I have identified annular flow as the primary regime associated with scale formation in both Patuha (steam-dominated) and Salak (water-dominated) systems. Critical flashing zones were precisely located at 1458.27 m (4784,35 ft) depth (Patuha) and 1402.08 m (4600 ft) depth (Salak), where pressure reductions initiate mineral precipitation. Both Hewitt-Robert manual calculations and

WellSim computational simulations consistently confirmed this finding, demonstrating that this flow pattern—characterized by liquid film on pipe walls with central gas flow—creates favorable conditions for mineral deposition regardless of reservoir type. This validated relationship provides specific monitoring parameters for early scaling intervention.

T2: Vapor-Dominated System Scaling Mechanisms and Non-Condensable Gas Influence

I foundthat vapor-dominated systems with 98% dryness remain susceptible to scaling through specific mechanisms. In Patuha, CO_2 degassing increases Calcite Saturation Index, promoting calcium carbonate precipitation despite limited water content. In Kamojang, rapid pressure drops (>1.2 bar/min) trigger silica deposition. Field measurements documented correlations between elevated non-condensable gases (CO_2 up to 95.84%, H_2S up to 3.25%), pressure reductions, and scale formation. These mechanisms indicate that high-dryness systems require specialized monitoring protocols focused on gas composition and pressure transition zones.

T3: Wellbore Geometry Transitions and Quantified Scale Impact on Production

I have quantifiedhow casing diameter changes between 7" perforated liner and 13⅜" production casing create localized flow disturbances that accelerate mineral deposition. In Kamojang, measured scale thickness of 251.8 mm reduced the effective wellbore diameter by 20%, resulting in 36% increased frictional pressure loss. This constriction accounted for approximately 75% of the observed 2.1 bar wellhead pressure decline despite only 8.9% mass flow reduction. These measurements established direct relationships between geometry transitions, scale accumulation, and production parameters, providing design criteria for new wells and intervention thresholds for existing ones.

T4: Field-Specific Mineralogical Signatures and Redox-Controlled Scale Composition

In my research, I determinedthe distinct scale mineralogy across fields: calcite in Patuha, amorphous silica in Salak, and silica/quartz with magnetite in Kamojang. XRD analysis of Kamojang samples revealed magnetite (Fe_3O_4) formation under reducing conditions at depth (230°C, 26.5 bar), while surface PHREEQC modeling predicted goethite/hematite under oxidizing conditions. This redox-dependency demonstrates that accurate scale characterization requires downhole sampling rather than surface analysis alone. These field-specific signatures enable customized inhibition strategies targeting the actual mineralogical composition present in each system.

T5: Dryness-Mineralogy Relationship and Silica Scaling Dynamics

My study demonstrated that system dryness alone does not determine scale mineralogy. Kamojang and Patuha both exhibit 98% dryness, yet develop different scale types: silica-magnetite in Kamojang versus calcite in Patuha. My research further established that pressure reduction rates directly influence silica morphology—rapid depressurization (>1.2 bar/min) produces crystalline quartz at Kamojang (900.74 m depth), while slower pressure decline leads to amorphous silica in Salak. These findings provide specific operational thresholds for predicting and potentially controlling scale morphology through pressure management.

T6: Feedzone Contribution Influence on Scale Formation

My analysis of Patuha and Salak demonstrated that zones with highest fluid contribution (e.g., 46% at 1,389-1,421 m in Patuha) directly correlate with enhanced scale formation due to increased mass flux and flow turbulence. This empirical relationship showed that scaling intensity can be predicted by mapping feedzone distribution and contribution rates. The finding suggests that targeted scale mitigation should focus on major feedzones rather than treating the entire wellbore uniformly, potentially improving intervention efficiency and reducing treatment volumes.

T7: Integrated Multi-Parameter Scaling Risk Assessment Framework

In my research, I developed a practical framework thatintegrats flow regime data, pressure-temperature profiles, fluid chemistry, and production history to predict scaling location and intensity. This approach addresses the multivariable nature of scale formation more effectively than single-parameter methods. Testing across multiple fields demonstrated improved predictive accuracy compared to conventional techniques. The framework allows operators to identify high-risk zones before production decline occurs, enabling preventive treatments at optimal timing and targeted locations.

T8: Cost-Effective Broaching Method Treatment Protocol for Vapor-Dominated Systems

I developed and validated in practice a modified broaching protocol for vapor-dominated systems that achieved 93-96% cost reduction (USD 42,690 versus USD 628,147-1,195,339) compared to conventional methods. Economic analysis showed payback periods of 3.3 months versus 4-10 years for traditional approaches, while maintaining comparable scale removal effectiveness. The optimized procedure addresses the specific mechanical and chemical requirements of silica-magnetite scales in high-temperature environments, providing an economically viable solution for maintaining well productivity

IV. List of Publications

Akhmad Sofyan MTMT ID: 10080019

IV.1. Articles Published and Used in the PhD Dissertation

Sofyan, A., Wiharti, S., Szanyi, J., Suranta, B.Y., Njeru, R. (2023). Determination of Scaling Zone and Scaling Type in Slotted Liner Based on the Fluid Flow Pattern in the Geothermal Well "X". International Journal of Renewable Energy Research, 28 March 2023. https://doi.org/10.20508/ijrer.v13i1.13603.g8681

Sofyan, A., Szanyi, J., Aka, H.S. (2023). Investigation of Zone and Type of Scaling Based on the Fluid Flow Pattern in the Geothermal Well "X" at the Salak Geothermal Field -- Indonesia. International Journal of Renewable Energy Research, 16 July 2023. https://doi.org/10.20508/ijrer.v14i1.14254.g8879

Sofyan, A., Jaya, R., Susanto, H., Njeru, R.M., Bozsó, G., Szanyi, J. (2025). Scale Treatment Planning Using Broaching Method in a Vapor-Dominated Geothermal Well X at Kamojang Geothermal Field. Eng publisher, April 2025. https://doi.org/10.3390/eng6040067

IV.2. Other Publications

Sofyan, A., Bujang, Y.D.G., Suranta, B.Y. (2023). Heat Loss Effect Analysis by Using JIWAFlow Wellbore Simulation in Geothermal Field Well-Y. American Institute of Physics (AIP), 8 May 2023. http://dx.doi.org/10.1063/5.0120544

Suranta, B.Y., **Sofyan, A.**, Khoiriarta, F., Handaja, S. (2023). Selection of Drilling Bit for the 12 ¼" Holes in The Geothermal Wells at The Company of XYZ. International Journal of Renewable Energy Research, 11 September 2023. https://doi.org/10.20508/ijrer.v14i4.14417.g8946

Suranta, B.Y., **Sofyan, A.**, Wicaksono, B.A. (2023). Pore pressure prediction as the anticipation of abnormal pressure in well X and Y. American Institute of Physics (AIP), 8 May 2023. https://doi.org/10.1063/5.0120746

Rosiani, D., Walay, M.G., Rahalintar, P., Candra, A.D., **Sofyan, A.**, Haratua, Y.A. (2023). Application of Artificial Intelligence in Predicting Oil Production Based on Water Injection Rate. International Journal on Advanced Science, Engineering and Information Technology, November 2023. https://doi.org/10.18517/ijaseit.13.6.19399

Suranta, B.Y., et al., **Sofyan, A.** (2023). Best Practices to Achieve Optimal Geothermal Drilling Performance in A Cost-Effective Manner: Case Study of the Fastest Geothermal Well Drilling in Java and Sumatra. Scientific Contributions Oil and Gas, 26 December 2023. https://doi.org/10.29017/SCOG.46.3.1591

Njeru, R.M., **Sofyan, A.**, Halisch, M., Kóbor, B., Szanyi, J. (2024). Optimizing Micro-CT Resolution for Geothermal Reservoir Characterization in the Pannonian Basin. Energies. https://doi.org/10.3390/en17133081

Rosiani, D., Zulfan, Suranta, B.Y., **Sofyan, A.** (2025). Machine Learning Classifies Data for Early Warning of Stuck Pipe Detection in Geothermal Drilling. International Journal on Advanced Science, Engineering and Information Technology, January 2025. https://doi.org/10.18517/ijaseit.15.1.20333

IV.3. List of Conferences

Sofyan, A., Muqtadir A., Aka H.S. Bujang, Y.D.G., Suranta, B.Y. (2021). Heat Loss Effect Analysis by Using JIWAFlow Wellbore Simulation in Geothermal Field Well-Y. 3rd Borobudur International Symposium of Science and Technology, Indonesia.

Sofyan, A., Wiharti, S. (2022). The Analysis of Horizontal Lip Pressure Production Test Method in Well X. European Geothermal PhD Day, Aachen, Germany.

Sofyan, A. (2022). The Effect of Casing Design on Well X Production in Geothermal Y Field Using JIWA Flow. 1st International Conference in Earth Sciences and Energy Transition, Muscat, Oman.

Sofyan, A., Wiharti, S., Szanyi, J., Suranta, B.Y., Njeru, R. (2023). Scaling Type and Scaling Zone Determination in Slotted Liner Based on the Fluid Flow Pattern in Geothermal Well X. European Geothermal PhD Day, Glasgow, UK.

Sofyan, A., Jaya, R.,. Njeru, R.M., Bozsó, G., Szanyi, J. (2024). Scaling Mitigation in Well X Using Broaching Method at the Vapour Dominated Geothermal Field. European Geothermal PhD Day, Delft, Netherlands.

Sofyan, A. (2025). Scale Formation and Treatment in Indonesian Geothermal Wells: A Multi-Field Comparative Analysis. European Geothermal PhD Day, Szeged, Hungary.

V. Co-authors' Declaration

V.1. Publication 1

We, the co-author of the publication: Sofyan, A., Wiharti, S., Szanyi, J., Suranta, B.Y., & Njeru, R. (2023). *Determination of Scaling Zone and Scaling Type in Slotted Liner Based on the Fluid Flow Pattern in the Geothermal Well "X".* International Journal of Renewable Energy Research., https://doi.org/10.20508/ijrer.v13i1.13603.g8681", officially declare that the jointly published results in the thesis and the publication are greatly contributed by the candidate and have neither heretofore been conscripted nor shall henceforth be requisitioned for the quintessential purpose of procuring academic laurels or scholarly appellations.

Date: Szeged (Hungary), 18 July 2025

Name and Signature of the co-authors:

Syafira Wiharti (Indonesia)

János Szanyi (Szeged – Hungary)

Bambang Yudho Suranta (Indonesia)

Rita Njeru (Kenya)

V.2. Publication 2

We, the co-author of the publication: Akhmad, S., Janos, S., & Hari, A. S. (2024). *Investigation of Zone and Type of Scaling Based on the Fluid Flow Pattern in the Geothermal Well "X" at the Salak Geothermal Field - Indonesia*. International Journal of Renewable Energy Research, 14(1), 192–202. http://doi.org/10.20508/ijrer.v14i1.14254.", officially declare that the jointly published results in the thesis and the publication are greatly contributed by the candidate and have neither heretofore been conscripted nor shall henceforth be requisitioned for the quintessential purpose of procuring academic laurels or scholarly appellations.

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Date: Szeged (Hungary), 18 July 2025

Name and Signature of the co-authors:

János Szanyi (Szeged – Hungary)

Hari Sumantri Aka (Indonesia)

V.3. Publication 3

We, the co-author of the publication: Sofyan, A., Jaya, R., Susanto, H., Njeru, R. M., Bozsó, G., & Szanyi, J. (2025). *Scale Treatment Planning Using Broaching Method in a Vapor-Dominated Geothermal Well X at Kamojang Geothermal Field*. Eng, 6(4), 67. https://doi.org/10.3390/eng6040067", officially declare that the jointly published results in the thesis and the publication are greatly contributed by the candidate and have neither heretofore been conscripted nor shall henceforth be requisitioned for the quintessential purpose of procuring academic laurels or scholarly appellations.

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Date: Szeged (Hungary), 18 July 2025

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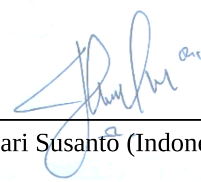
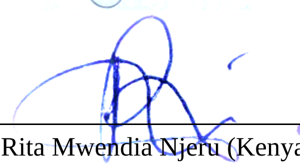


Hari Susanto (Indonesia)



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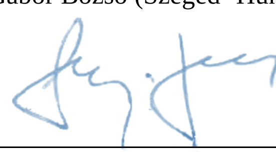

János Szanyi (Szeged – Hungary)

VI. DECLARATION OF THE SUPERVISOR

I, **János Szanyi**, hereby confirm that the content of the dissertation titled "*Scale Formation and Treatment Plan in Indonesian Geothermal Wells*" is based on the independent work of **Akhmad Sofyan**, the doctoral candidate. Akhmad has made a decisive contribution to the results presented in this dissertation through her independent and creative research efforts. I consider the entire dissertation to be of high academic and professional quality, and I fully support its submission for review and acceptance.

Szeged (Hungary), 18th July 2025

Dr. János Szanyi,
PhD Supervisor

VII. DECLARATION OF THE CO-SUPERVISOR

I, **Gábor Bozsó**, hereby confirm that the content of the dissertation titled "*Scale Formation and Treatment Plan in Indonesian Geothermal Wells*" is based on the independent work of **Akhmad Sofyan**, the doctoral candidate. Akhmad has made a decisive contribution to the results presented in this dissertation through her independent and creative research efforts. I consider the entire dissertation to be of high academic and professional quality, and I fully support its submission for review and acceptance.

Szeged (Hungary), 18th July 2025

Dr. Gábor Bozsó,
PhD Co-supervisor