

Emerging Trends in Engineering and Sustainability

A quarterly Peer-Reviewed Scientific Journal
Published by Al-Naji University



Volume 2 | Issue 3 | 2026

Deposit number at the National Library in Baghdad 2922 for 2025

About Journal

Emerging Trends in Engineering and Sustainability (ETES) is a peer-reviewed, open-access scientific journal published by **Al-Naji University** in alignment with the academic standards and publishing regulations of the **Ministry of Higher Education and Scientific Research in Iraq**.

ETES is dedicated to the dissemination of high-impact research and the promotion of innovative practices across all fields of engineering, with a strong emphasis on sustainability. The journal welcomes **original research articles and review papers** that contribute to advancing sustainable solutions, technologies, and methodologies relevant to engineering disciplines.

To ensure academic rigor and scholarly integrity, ETES employs a **double-blind peer review process** involving at least two independent external reviewers for each submission. The journal adheres strictly to the ethical guidelines set forth by the **Committee on Publication Ethics (COPE)**.

As an **open-access** journal, ETES provides immediate and unrestricted access to all published articles. Readers may freely read, download, and distribute full-text content without requiring prior permission from authors or the publisher, supporting global knowledge sharing.

ETES follows a **quarterly publication schedule**, with four issues released annually. The journal is committed to becoming a reputable international platform for scholars and researchers working at the intersection of engineering innovation and sustainable development.

ETES published **quarterly**, with **four** regular issues released each year. The journal's long-term vision is to be widely indexed, cited, and read by a global scholarly community, contributing meaningfully to the advancement of sustainable engineering solutions worldwide.

Aims

Emerging Trends in Engineering and Sustainability (ETES) is an international, open-access, peer-reviewed journal committed to advancing innovation and sustainability across all disciplines of engineering. The journal seeks to serve as a platform for disseminating high-quality, original research and comprehensive reviews that address contemporary challenges and transformative practices in engineering with a focus on sustainable development. ETES aims to foster intellectual exchange among researchers, academics, professionals, and postgraduate students by promoting interdisciplinary collaboration and publishing research that contributes to the evolution of sustainable engineering practices worldwide.

Scope / Categories

ETES welcomes submissions of original research articles and scholarly review papers that explore emerging concepts, methodologies, and technologies in the diverse fields of engineering, particularly those that contribute to sustainability. The journal encourages contributions that reflect rigorous scientific inquiry, innovative thinking, and practical applications.

Core areas of interest include, but are not limited to:

- Mechanical Engineering
- Petroleum Engineering
- Chemical Engineering
- Environmental Engineering
- Sustainability and Green Technologies
- Electrical and Electronic Engineering
- Computer Science, Software Engineering, and Informatics
- Structural and Geotechnical Engineering
- Engineering Management and Decision-Making
- Transportation and Infrastructure Engineering
- Water Resources and Hydraulic Engineering
- Architectural Design and Urban Sustainability
- Energy Systems and Power Engineering
- Advanced Materials and Materials Engineering
- Control Systems, Electronics, and Signal Processing
- Communication and Networking Technologies
- Renewable and Clean Energy Technologies
- Civil Engineering

ETES is committed to publishing research that bridges theory and practice, fosters interdisciplinary solutions, and contributes to sustainable development goals (SDGs) in engineering contexts.

Editorial Board

Prof. Dr. Hatem K. Breesam, Editor-in-Chief
College of Engineering, Al-Naji University,
Baghdad, Iraq

Expertise: Construction Management, Project management, economy, sustainability, planning, management, risk management
Email: hatem.khaleefah@alnaji-uni.edu.iq

Prof. Dr. Alhassan H. Ismail, Managing Editor

Department of Water Resource Techniques,
Institute of Technology, Middle Technical University, Baghdad, Iraq
Expertise: Water Quality
Email: alhassan_hayder@mtu.edu.iq

Editorial Board Members

Prof. Dr. Moneer Hameed Tolephih
College of Engineering, Al-Naji University,
Baghdad, Iraq
Expertise: Mechanical Engineering, Renewable Energy, Sustainability
Email: monerht@alnaji-uni.edu.iq

Asst. Prof. Dr. Omar Al-Fatlawi
College of Engineering, Al-Naji University,
Baghdad, Iraq
Expertise: Geoscience, Gas Engineering, Reservoir Simulation, Petroleum Engineering
Email: omar.al-fatlawi@alnaji-uni.edu.iq

Prof. Dr. Riadh Al-Mahaidi
Department of Civil and Construction Engineering, Swinburne University of Technology, Melbourne, Australia
Expertise: Civil Engineering, Concrete, Steel, Fiber Reinforced Polymers
Email: ralmahaidi@swin.edu.au

Associate Prof. Dr. Harith Hasoon Al-Moameri
Materials Engineering Department, Mustansiriyah University, Baghdad, Iraq
Expertise: Polyurethane, Polymer, Blowing Agent, Simulation, Building Materials
Email: almoamerih@uomustansiriyah.edu.iq

Prof. Dr. Hamed Karami

Department of Signal and Information Processing for Sensing Systems Institute for Bioengineering of Catalonia, Spain

Expertise: Gas Sensors, Signal Processing, Drying Technology, Food Quality and Control
Email: hkarami@ibecbarcelona.eu

Associate Prof Dr. Nizar F.O. Al-Muhsen

Department of Power Mechanics, Technical Instructors Training Institute (TITI), Middle Technical University (MTU), Baghdad, Iraq

Expertise: Bio-Fuel Combustion and Emissions, Internal Combustion Engines, Renewable and Sustainable Energy Systems.
Email: nizar.almuhsen@mtu.edu.iq

Prof. Dr. Mazen J. Al-Kheetan

Civil and Environmental Engineering Department, College of Engineering, Mutah University, Karak, Jordan

Expertise: Sustainability in construction, low-carbon cementitious materials, concrete, asphalt materials, additive manufacturing, pavement
Email: mazen.al-kheetan@mutah.edu.jo

Prof. Dr. Ali Kadkhodaie

Earth Sciences Department, Faculty of Natural Sciences, University of Tabriz, Tabriz, Iran

Expertise: Formation Evaluation, Petrophysics, Petroleum Geology.
Email: kadkhodaie_ali@tabrizu.ac.ir

Prof. Dr. Ali Al-Ataby

Chair and Associate Professor, Electrical and Electronics Engineering, School of Engineering & Computer Science, AURAK, Ras Al Khaimah, UAE

Expertise: Signal/Image Processing, Machine Learning/AI, Robotics, IoT Sensors.
Email: ali.ataby@aurak.ac.ae

Prof. Dr. Hussein Znad

Chemical Engineering, Curtin University, Perth, Australia

Expertise: microalgae, resources recovery, wastewater treatment, CO₂ mitigation, biofuel production (biohydrogen and biodiesel), Functionalized nanomaterials.
Email: h.znad@curtin.edu.au

Asst. Prof. Dr. Dhifaf Jaafar Sadeq

Department of Petroleum Engineering,
Al-Naji University, Baghdad, Iraq

Expertise: Gas Engineering, Gas Hydrate, Flow Assurance, Petroleum Production Engineering.

Email: dhifaf.jaafar@alnaji-uni.edu.iq

Prof. Dr. Ahmed Razzaq Hasan Al-Manea

Al-Rumaitha Technical Institute, Al-Furat Al-Awsat Technical University, Najaf, Iraq

Expertise: Solar energy, sustainability, Finite Element Analysis, CFD, Simulation and Modeling, Computational Simulation.

Email: Dr.ahmed.almanea@atu.edu.iq

Prof. Dr. Hussein A Kazem

Faculty of Engineering, Sohar University, Sohar, Oman

Expertise: Solar Thermal, Photovoltaic, Renewable Energy, Dust, Photovoltaic / Thermal, Nano-PCM

Email: H.Kazem@su.edu.om

Prof. Dr. Satiye Korkmaz

Department of Photonics and Optoelectronics, Electrical and Electronics Engineering, Faculty of Engineering, Karabuk University, Karabuk, Turkey

Expertise: Nanotechnology, Energy storage, Photonics, Optoelectronics.

Email: satiyekorkmaz@karabuk.edu.tr

Prof Dr. Makram A. Fakhri

Department of Laser Engineering and Electronic Optics, University of Technology-Iraq, Baghdad, Iraq

Expertise: Nano materials, Nanostructures, Optoelectronics devices, Photonics devices, Photonics crystals, sensors, lasers, photodetectors.

Email: Makram.a.fakhri@uotechnology.edu.iq

Asst. Prof. Dr. Samar Sabie

Faculty of Information, University of Toronto, Toronto, Canada

Expertise: Climate Change, Building Automation Systems, Social Sustainability.

Email: samar.sabie@utoronto.ca

Prof. Dr. Ahmed Falh Hasan

Department of Materials Engineering, University of Diyala, Diyala, Iraq

Expertise: Materials design and Engineering

Email: ahmed_hasan_eng@uodiyala.edu.iq

Dr. Fahd Saeed Alakbari

Interdisciplinary Research Center for Hydrogen Technologies and Carbon Management, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

Expertise: Machine learning applications in engineering, Drilling fluid engineering, Carbon dioxide capture, utilization, and storage

Email: fahd.akbari@kfupm.edu.sa

Assoc. Prof. Dr. Mohammed N. Abdulrazaq Alshekhly

Chair of University Research Council, Gulf University, Kingdom of Bahrain

Expertise: Robotics, IoT, Smart Cities, Metaverse, Sustainability, Metal processing

Email: dr.mohammed.alshekhly@gulfuniversity.edu.bh

Prof. Dr. Mofazzal Hossain

Western Australian School of Mines (WASM), Energy Engineering, Curtin University, Perth, Australia

Expertise: Computational modelling; fluid flow stimulation, design and optimization of hydraulic fracturing;; well design and geomechanical analysis.

Email: md.hossain@curtin.edu.au

Asst. Prof. Ghamgeen Izat Rashed

School of Electrical Engineering and Automation, Wuhan University-China

Expertise: FACTS devices, Reliability of power System, Renewable energy, Smart Grid

Email: ghamgeen@whu.edu.cn

Proofreading**Prof. Dr. Dima F. Ameen**

Department of English, College of Education, Al-Naji University, Baghdad, Iraq

Production**Rawan Nihad Al-Sammarraie**

Al-Naji University, Baghdad, Iraq

Publication Ethics

Emerging Trends in Engineering and Sustainability (ETES) is dedicated to maintaining the highest standards of research integrity and academic publishing. As an adherent to the principles established by the Committee on Publication Ethics (COPE), ETES strictly follows COPE's guidelines in addressing ethical concerns and potential misconduct.

Authors submitting to ETES are expected to uphold the principles of ethical research and responsible authorship. Misrepresentation of data, results, or authorship undermines the credibility of the journal, damages the scholarly record, and erodes public trust in science. To preserve the integrity of academic publishing, authors must comply with the following ethical standards:

Originality and Exclusivity: Manuscripts must be original and should not be under review by another journal simultaneously. Submissions must not have been previously published, either in part or in full, in any language or format, unless the new manuscript represents a significant extension of prior work. In such cases, authors must clearly disclose previous publications to avoid self-plagiarism and text recycling.

Justified Secondary Publication: In rare and justified cases, secondary or concurrent publication (e.g., translated work or work adapted for a distinct audience) may be permitted, provided that all conditions for ethical secondary publication are met and transparent disclosure is made.

Avoidance of Redundant Publication: Fragmentation of a single research project into multiple submissions ("salami publishing") solely to increase publication count is discouraged and considered unethical.

Proper Attribution and Avoidance of Plagiarism: All sources, data, theories, and text derived from other authors must be appropriately cited. Verbatim quotations must be placed within quotation marks and accompanied by citations. Any reuse of copyrighted material must be supported by proper permission and acknowledgment.

Accuracy and Transparency: Authors must present their findings clearly, accurately, and honestly, without data fabrication, falsification, or inappropriate manipulation (including of images). Field-specific standards for data collection and analysis should be rigorously followed.

By submitting a manuscript to ETES, authors affirm their commitment to ethical conduct in research and publication. Non-compliance may result in manuscript rejection, retraction of published articles, or notification of institutional misconduct boards, as deemed appropriate by the editorial team.

Plagiarism and AI Policy

Emerging Trends in Engineering and Sustainability (ETES) is committed to upholding the highest standards of academic integrity, originality, and responsible authorship. All submitted manuscripts are rigorously screened for plagiarism using Turnitin (<https://www.turnitin.com/>). Plagiarism—including textual duplication, data fabrication or falsification, duplicate submissions, and improper attribution of authorship—constitutes a serious breach of ethical publishing practices and will not be tolerated. Concurrent submission of the same manuscript to multiple journals is also strictly prohibited.

To maintain scholarly integrity, manuscripts must have an overall similarity index below 20%, with no more than 5% similarity from any single source. It is the responsibility of the author(s) to ensure these thresholds are met and sustained throughout the review and publication process. While similarity reports provide a quantitative measure of textual overlap, legitimate citations and common academic language may contribute to the score. Therefore, editorial judgment is essential in interpreting these reports to determine if ethical concerns are warranted.

ETES maintains strict guidelines regarding the use of artificial intelligence in scholarly writing. The use of generative AI tools for drafting, composing, or editing the intellectual content of a manuscript is not permitted. Manuscripts must reflect the original work and critical thinking of human authors. Authors are required to confirm, upon submission, that the content has not been produced or substantively modified by AI tools. Minor AI-assisted improvements for grammar or language clarity are acceptable, but their use

should not compromise the authenticity or originality of the research. AI-generated images are generally prohibited unless explicitly disclosed, clearly labeled, and appropriately cited.

Open Access

In alignment with the principles of transparency, accessibility, and knowledge dissemination upheld by Emerging Trends in Engineering and Sustainability (ETES), all published articles are made freely available to the public without any subscription or access fees. The journal operates under the Creative Commons Attribution 4.0 International License (CC BY 4.0) [<https://creativecommons.org/licenses/by/4.0/legalcode>], which permits users to freely access, download, reproduce, distribute, and share the full content of the articles in any format or medium. Furthermore, readers may link to, index, or utilize the articles for scholarly purposes, provided that appropriate credit is given to the original author(s) through proper citation.

Authors retain full copyright of their published work, while ETES ensures that their intellectual contributions receive due recognition in accordance with the licensing terms. This licensing framework fosters open scientific communication and encourages the broad dissemination and reuse of research in engineering and sustainability, supporting global efforts towards sustainable development and innovation.

Guidelines for Authors

Manuscript Preparation

Emerging Trends in Engineering and Sustainability (ETES) is a multidisciplinary, double-blind, peer-reviewed journal committed to publishing high-quality research that spans all areas of engineering, with a particular emphasis on innovations that promote sustainability. The journal strictly adheres to the ethical guidelines set forth by the Committee on Publication Ethics (COPE) to maintain the integrity of the scholarly record. To ensure originality, all submissions undergo thorough screening using advanced plagiarism detection software. Authors are expected to disclose any potential conflicts of interest in their cover letter. Manuscripts that do not comply with the journal's *Instructions for Authors* will not be considered for further processing.

Submission Declaration and Verification

By submitting a manuscript to *Emerging Trends in Engineering and Sustainability (ETES)*, authors affirm that the work is original and has not been previously published, except in limited forms such as abstracts, academic theses, or invited lectures. The submission must not be under review or consideration by any other journal or publication outlet. Furthermore, all listed authors must have approved the submission, and, where applicable, authorization must be granted by the relevant institutional or organizational authorities where the research was conducted. Authors also agree that, if accepted, the manuscript will not be published elsewhere in the same or substantially similar form, in English or any other language, including electronic platforms. To ensure adherence to these standards, all submissions may be subjected to plagiarism and duplication checks using Crossref Similarity Check and other recognized originality verification tools.

Language and Manuscript Submission

Manuscripts submitted to *Emerging Trends in Engineering and Sustainability (ETES)* must be written in clear, high-quality English. Either American or British English is acceptable, but consistency in spelling and usage must be maintained throughout the manuscript. Authors may use AI-assisted tools strictly to enhance grammar and readability; however, the intellectual content, structure, and originality of the manuscript must remain the authors' own.

Peer Review Policy

Emerging Trends in Engineering and Sustainability (ETES) adheres to a double-blind peer review process to ensure objectivity, fairness, and academic integrity. In this model, the identities of both authors and reviewers are concealed throughout the review process. All submitted manuscripts are typically evaluated by a minimum of two independent experts with relevant subject-matter expertise, who assess the originality, scientific merit, methodological soundness, and relevance of the work.

The final decision regarding the acceptance, revision, or rejection of a manuscript lies solely with the Editor, who considers reviewers' feedback alongside the manuscript's alignment with the journal's scope and quality standards. All editorial decisions are final.

To maintain transparency and avoid conflicts of interest, Editors are excluded from the review and decision-making process for manuscripts in which they have a personal, professional, or financial interest—including submissions authored by themselves, their colleagues, or family members. In such cases, an independent editor will be assigned to oversee the peer review process to uphold the journal's ethical standards.

Template Compliance

All authors are required to prepare and submit their manuscripts in strict adherence to the *Emerging Trends in Engineering and Sustainability (ETES)* manuscript template. The template has been designed to ensure consistency, clarity, and a professional appearance across all submissions. Authors must carefully follow all formatting guidelines, including the prescribed font styles, section headings, and layout specifications.

Under no circumstances should the template's header, footer, page size, or margin settings be altered. These elements are essential for maintaining uniformity in the publication process.

Additionally, all figures, tables, and equations are should be embedded appropriately within the template and labeled according to the ETES style guide.

In addition to the manuscript, author(s) are required to submit the followings:

- Cover letter
- Title Page
- Copyright Form.

Authors must ensure that their full names and institutional affiliations are presented accurately and consistently in the manuscript, as specified in the ETES template. Affiliations should include the department (if applicable), institution or university, city, and country. This information must appear directly below each author's name as formatted in the template.

Generative AI Policy for Authors

Emerging Trends in Engineering and Sustainability (ETES) upholds the highest standards of research integrity, originality, and authorship. In alignment with these principles, the use of generative AI or AI-assisted technologies for drafting, writing, or substantively editing the content of a manuscript is strictly prohibited. Authorship entails full intellectual responsibility for the work submitted, including its conception, methodology, analysis, interpretation, and written expression—responsibilities that cannot be delegated to non-human tools.

Manuscripts must be the product of human scholarly effort and critical thinking. Text generated by AI, even when used for language refinement or content development, poses significant risks of inaccuracy, bias, lack of originality, and potential plagiarism. Furthermore, reliance on such tools may obscure issues related to authorship attribution and accountability.

Authors are required to affirm, upon submission, that the manuscript has been written entirely by the listed authors without the use of generative AI tools. Failure to comply with this policy may result in the rejection of the submission or retraction of the published article, in accordance with the journal's ethical guidelines and the standards of the Committee on Publication Ethics (COPE).

The use of **AI-generated images** is generally not allowed unless explicitly disclosed in the captions and subject to thorough review. Authors must ensure that any such images are clearly identified and accompanied by appropriate citations and permissions, as necessary.

Authors should only use the AI-assisted technologies for enhancing readability and language of their manuscript.

AI Declaration Statement

The authors are responsible for completing the **AI Declaration Statement** in ETES word Template. The **statement is:** “The authors confirm that the manuscript has been written without the assistance of generative AI or AI-based writing tools.”

ETES Copyright and License Agreement (Open Access – CC BY 4.0)

Title of Paper/Article:

Contributing Author(s):

i. License of Publishing Rights

I (we), the undersigned author(s), hereby grant to the Emerging Trends in Engineering and Sustainability (ETES) an exclusive license to publish the above-titled article in all formats (print, electronic, and future technologies), in all languages and media, worldwide, for the full duration of copyright. This includes the right to reproduce, archive, disseminate, and distribute the Article, and to authorize others to do so for scholarly purposes.

The author(s) retain full copyright in the Article.

ii. Open Access and Licensing

The Article will be published under the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0).

This license permits others to:

- Share — copy and redistribute the material in any medium or format
- Adapt — remix, transform, and build upon the material for any purpose, including commercial use

As long as appropriate credit is given to the original author(s), a link to the license is provided, and it is clearly indicated if changes were made.

License link: <https://creativecommons.org/licenses/by/4.0/>

iii. Author Reuse Rights

The author(s) retain the right to:

- Reuse the Article in their own future works (books, compilations, theses, etc.)
- Deposit the Article in institutional or subject repositories
- Share the Article via personal websites or academic networks
- Use the Article for teaching, presentations, and other academic purposes

All reuse must credit the original publication in ETES and include a link to the published version and CC BY license.

iv. Supplemental Materials

If any Supplemental Materials (e.g., data sets, videos, software, enhanced graphics) are submitted along with the Article, ETES has the non-exclusive right to publish and link to these materials in any media or format.

The author(s) confirm they have secured all necessary permissions for such materials.

v. Reversion of Rights

If the Article is not accepted for publication or is withdrawn prior to acceptance, this license agreement becomes null and void. However, ETES may retain a non-public archival copy for record purposes.

vi. Revisions and Addenda

No changes to this License Agreement shall be valid unless confirmed in writing by ETES. This agreement supersedes any prior agreements regarding the Article.

vii. Warranties and Author Declarations

The author(s) declare that:

- The work is original and has not been published elsewhere,
- All co-authors have reviewed and approved the manuscript,
- The Article does not infringe any copyright, patent, or other rights,
- Necessary permissions for third-party materials have been obtained,
- There are no undisclosed conflicts of interest.

viii. Indemnification

The author(s) agree to indemnify and hold harmless ETES from any claims, damages, or expenses arising from a breach of the above warranties.

ix. Joint Authorship

For jointly authored works, all authors must sign this agreement, or one author must sign with authority on behalf of all listed authors.

Author's Name	Signature	Date

Contents

Volume 02, No. 02 (2026)

Paper Title	Pages
Comparative Analysis of Network Unavailability Rate (NUR) Equations in Modern 4G/5G Networks	1-9
Muna Mahdi Salih and Yousif Qays Alaraji	
Reservoir Porosity Prediction in the Koroshina Dolomite Formation, Sadad Gas Field, Syria, Using Seismic Inversion and Artificial Neural Networks	10-24
Wasim Ali Alrhaiyel	
Improvement Proposals of Al-Kansaa Intersection	25-38
Miami M. Hilal, Sarab Mehdy, Nahla M Salim	
Strength of Clay Treated with Biopolymer Under Cyclic Wetting and Drying	39-51
Mohammed Y. Fattah, Mohammed F. Aswad, Nahla M. Salim, Teba A. Abd	
Influence of Skirt Length and Foundation Size on the Bearing Capacity of Circular Foundations Resting on Sandy Soil	52-64
Kawther Y. H. Al-Soudany, Nahla M. Salim, Luay Y. Hussein	



Comparative Analysis of Network Unavailability Rate (NUR) Equations in Modern 4G/5G Networks

Muna Mahdi Salih^{1*} and Yousif Qays Alaraji²

¹ Cybersecurity Engineering Department, Engineering College, Al-Naji University, Baghdad, Iraq.

² Artificial Intelligence Engineering Department, Al-Naji University, Baghdad, Iraq.

Article Info	ABSTRACT
Received: 12 July 2026 Revised: 12 Sep. 2026 Accepted: 17 Sep. 2026 Available online: 30 Sep. 2026 Keywords: Network Availability; Network Unavailability Rate; Mean Time Between Failures; Mean Time to Repair; Reliability Engineering; Telecommunications; Operations Support Systems; Network Reliability.	Despite strict industry commitments to network uptime, engineers have yet to settle on a single, universally accepted method for computing the Network Unavailability Rate (NUR). This paper derives and comparatively evaluates five NUR formulations — the classical uptime ratio, MTBF/MTTR-based reliability model, failure-rate (λ) approximation, Erlang queuing model, and the telecom cell-based model — within a unified analytical-simulation environment applied to LTE/5G networks. A Monte-Carlo framework was constructed over a synthetic topology of 1,000 cells across 50 replications to isolate each model's sensitivity to MTTR, failure rate, and spatial burst failures. Measured against the realised per-cell unavailability of the simulated traces ($NUR_{true} = 0.0035$), the classical model deviates by -22.9%, the MTBF/MTTR, λ, and Erlang formulations occupy an intermediate band of -12.0% to -9.0%, and the cell-based telecom formulation tracks the simulated ground truth most closely (deviation $\approx -2.8\%$ under the tested parameter ranges) by preserving inter-cell heterogeneity that aggregate formulations average out. These findings point toward cell-level KPI aggregation as the preferred basis for SLA monitoring and reliability engineering in contemporary and forthcoming 5G deployments.

1. Introduction

Modern cellular networks are expected to meet brutal uptime targets over thousands of dispersed nodes. But as networks crowd closer together, maintaining these tight availability targets becomes a massive scaling challenge [1]. While operator reports routinely cite aggregate uptime figures above 99.9%, such values conceal important spatial and temporal variation that classical reliability models tend to suppress [2].

Service level agreements in modern LTE and 5G contracts formalize availability expectations that carriers are contractually bound to meet [3]. Network operators, vendors, and standards bodies all define NUR differently—and that lack of

alignment makes true cross-network benchmarking virtually impossible [4]. This modeling gap becomes a critical vulnerability during cascading base-station outages; if a framework ignores these spatial correlations, it will produce highly overoptimistic estimates of true network downtime [11].

Several foundational contributions frame the present discussion. Cholda et al. [1] introduced quality-of-resilience as a quantitative extension of QoS, providing a reliability characterization tool that goes beyond simple uptime ratios. Netes [2] examined how evolving network architectures alter dependability characteristics that classical formulations were not designed to handle. The foundational clarity of the present NUR taxonomy relies heavily on work by Al-Kuwaiti et al. [3],

who mapped out the precise distinctions between dependability, fault tolerance, reliability, and survivability. On the operational side, Snow et al. [5] documented availability and survivability challenges specific to wireless and mobile environments, while field data from Bothwell et al. [6] quantified MTBF and MTTR at the base-transceiver level. More recent empirical work by Lazar et al. [9] and standardization efforts by Caso et al. [10] reinforce that effective KPI monitoring demands real-time, cell-granular measurement pipelines.

Four broad NUR model families are identified and examined here. First, classical models derive unavailability from the ratio of cumulative downtime to total observation time—a straightforward but spatially blind approach [5]. Second, reliability-engineering formulations rest on MTBF/MTTR statistics from hardware testing and field campaigns [6]. Third, failure-rate (λ) models treat each cell outage as an independent Poisson process [11]. Finally, the telecom-focused cell-based models pull together performance indicators for each individual cell, following the 3GPP monitoring standards [4]. This approach lines up with the OSS data streams that operators are already gathering [9], [10].

This paper is structured as follows: Section 2 reviews the related literature, and Sections 3 through 7 present the different NUR formulations along with the assumptions underlying each. Section 8 describes the Monte-Carlo simulation methodology. Section 9 presents and interprets comparative results. Section 10 draws conclusions and provides practical recommendations.

2. Related Work

Early analytical treatments of cellular reliability relied on classical fault-tree and Markov-chain methods. Looking at future cellular layouts, Farooq et al. [11] used continuous-time Markov chains to show that repair discipline—not just raw failure rate—drives steady-state availability. Real-world networks rarely follow idealized theory. Passive measurements by Baltrunas et al. [12] proved that actual outage patterns break away entirely from homogeneous Poisson expectations. A nationwide analysis by Li et al. [13] reinforces this spatial unpredictability, showing that failure rates vary wildly by location instead of spreading out evenly across the map. In

parallel, Hobler et al. [14] examined 5G networks and demonstrated how physical-layer channel availability can diverge from higher-layer reliability measures under bursty interference, a distinction especially relevant for URLLC services. Emara et al. [15] extended this perspective to a space-time model treating availability as a function of both time and deployment geometry—a perspective directly relevant to the cell-based formulation of Section 7.

Service-level availability measurement was addressed by Turkka and Foo [16], who proposed standardized procedures for 5G communication service availability.

“Kaja et al. [17] applied matrix-exponential distributions to study how cellular networks withstand disaster conditions. In parallel, Gautam and Dharmaraja [18] broke down the LTE-A architecture into stochastic sub-systems to assess reliability more precisely. Building on these perspectives, Kogan and Tarapore [19] proposed the Mean Time Between Outages (MTBO) as a way to capture production-level failure rates. Li et al. [20] extended the discussion to high-mobility 5G environments, showing that handover failures can make a significant contribution to overall NUR. Shifting from reactive fault mitigation, Ijaz et al. [21] implemented multi-parameter optimization architectures to demonstrate that proactive reliability management, driven by predictive KPI models, yields significantly higher network stability.

Against this backdrop, the present work contributes a systematic side-by-side derivation and Monte-Carlo evaluation of all five model families under identical network conditions—a controlled comparison that, to the authors' knowledge, has not been performed previously at this scale and granularity.

3. Classical Network Unavailability Rate Model

The classical model defines NUR as the fraction of elapsed calendar time during which the network, or a representative element within it, is out of service:

$$NUR = \frac{T_{(down)}}{T_{(total)}} \quad (1)$$

where T_{down} is the cumulative outage duration and T_{total} is the observation window.

This follows directly from the classical availability ratio $A = T_{(up)}/T_{(total)}$, so that $NUR = 1 - A$. Its principal strength is computational transparency: only outage logs, routinely stored by every operator's OSS, are required. Snow et al. [5] documented the wide adoption of this metric across wireless networks precisely because no distributional assumption about failure or repair processes is needed.

The formulation's main weakness is spatial aggregation. Treating the entire network as a single entity obscures whether downtime is concentrated in chronically failing cells or distributed uniformly — a distinction with direct consequences for maintenance resource allocation. Field evidence from Bothwell et al. [6] illustrated this limitation when aggregate site availability figures masked localized clusters of high-MTTR base stations. The classical model will therefore set the lower bound of NUR estimates in subsequent comparisons, consistent with its known tendency to underestimate true unavailability in heterogeneous deployments.

4. MTBF/MTTR-Based Reliability Model

Hardware-reliability engineering expresses unavailability through the ratio of mean repair time to the combined failure-and-repair cycle. Defining Mean Time Between Failures (MTBF), Mean Time to Failure (MTTF), and Mean Time to Repair (MTTR):

$$NUR = \frac{MTTR}{(MTTF+MTTR)} \quad (2)$$

$$MTBF = MTTF + MTTR \quad (3)$$

so that $NUR = MTTR/MTBF$. This approach emphasizes hardware performance over broad operational logs, drawing on component test data and real repair records to assess reliability at the equipment level. For instance, Bothwell et al. [6] reported MTBF values derived from large BTS fleets at Motorola, demonstrating that MTTR variability — not the failure-initiation rate — is the dominant driver of site-level unavailability.

From a network-management perspective, MTTR subsumes queuing effects (technicians awaiting dispatch), parts logistics, and access restrictions that can extend a nominally short repair to several hours in practice. Empirical studies confirm MTTR is a stronger predictor of

NUR than raw failure rate [6], [19]. The model therefore highlights maintenance-process efficiency as a primary lever for reliability improvement — an insight the classical ratio model is structurally unable to expose.

5. Failure-Rate (λ) Approximation Model

Assuming cell failures follow a homogeneous Poisson process with rate λ and repair durations are exponentially distributed with rate μ , steady-state unavailability takes the compact form:

$$NUR = \frac{\lambda}{(\lambda+\mu)} \quad (4)$$

This formulation is mathematically equivalent to the familiar MTBF/MTTR relationship (where $MTTF = 1/\lambda$ and $MTTR = 1/\mu$ for exponential cases). The benefit of formulating it in terms of instantaneous rates is that it allows sensitivity analysis, particularly when λ is obtained from operational event logs rather than from controlled laboratory experiments. If the intervals between failures are distributed exponentially, this approximation remains closely valid—an observation consistent with the Markov-chain modeling approach implemented by Farooq et al [11].

The Poisson-exponential assumption breaks down when correlated burst failures dominate — as occurs during grid outages or severe weather events disabling multiple co-located cells simultaneously. In such regimes, the λ model still yields a useful first-order estimate, but it structurally cannot capture spatial correlation [12], [13]. This limitation is quantified in the simulation study of Section 8.

6. Erlang Queuing-Based NUR Model

Telephone traffic engineering has long used the Erlang-B formula to characterize blocking probability in finite-capacity service systems. Applying the M/M/c/c loss model, the probability that a service request is blocked — and the network is therefore unavailable from the user's perspective — is:

$$NUR_{(Erlang)} = B(A, c) = (A^c/c!)/\sum_{k=0}^c (A^k/k!) \quad (5)$$

where $A = \lambda/\mu$ is the offered traffic intensity in Erlangs and c is the number of available repair crews. Eklundh [8] analyzed channel utilization and blocking probability in cellular systems with directed retry, establishing that blocking behavior is well captured by this formula even under non-symmetric load conditions.

Mapping the cellular repair workflow onto a queuing model is non-trivial: 'servers' represent field-maintenance teams, 'customers' are failed cells awaiting dispatch, and 'blocking' corresponds to a cell remaining offline because no crew is free [8]. Baltrunas et al. [12] provided measurement data showing that multi-hour outage tails often result from maintenance-queue saturation rather than the actual repair time itself. This evidence underscores how the Erlang model captures the impact of limited crew availability on repair delays—an aspect of unavailability that the classical and λ models are unable to reflect.

7. Telecom Cell-Based NUR Model

The cell-based approach evaluates KPIs at the level of individual cells rather than treating the network as a single aggregate. For a system of N cells observed over a period T , the unavailability is given by:

$$NUR_{cell} = \frac{1}{N} \sum_{i=1}^N \frac{T_{down,i}}{T_i} \quad (6)$$

where $T_{down,i}$ is the outage duration and T_i the observation period for cell i . This can also be expressed in terms of per-cell failure and repair statistics:

$$NUR_{cell} = \frac{1}{N} \sum_{i=1}^N (\lambda_i \cdot MTTR_i) \quad (7)$$

Because operators already collect cell-level event logs through OSS performance management systems, the inputs required for Equation (7) are directly available.

Wang et al. [7] proposed an NMS/OSS architecture for 5G Open RAN that exposes per-cell reliability counters compatible with this computation. Cho et al. [4] demonstrated that AI-enabled KPI monitoring pipelines deliver cell-granular failure diagnostics at operational timescales, and Lazar et al. [9] validated a real-time KPI measurement method whose outputs can be applied directly to Equation (7). Looking at each cell individually in Equation (6) makes it possible to reflect spatial differences in failure

behavior that would be lost in a network-wide average. For instance, when a burst failure disables a cluster of neighboring cells, each node records a higher $T_{down,i}$, rather than the effect being smoothed out in an average. Al-Kuwaiti et al. [3] highlighted that evaluating dependability at fine operational granularity provides a more faithful view of service disruption than broad aggregate metrics. While Equation (7) does not explicitly evaluate distance-based spatial correlation matrices, its cell-granular structure retains localized variance, ensuring that spatially clustered outages recorded in OSS event logs contribute fully to the total network calculation without being diluted by network-wide spatial averaging. In the same vein, Caso et al. [10] emphasized that QoS/QoE frameworks must operate at cell granularity to satisfy 5G SLA requirements. Taken together, these insights explain why the cell-based model achieves the lowest simulation error reported in Section 9.

8. Simulation Methodology

A Monte-Carlo engine was developed to evaluate the five NUR formulations under controlled, identical network conditions. The simulated network comprised 1,000 LTE/5G cells observed over a nominal one-month window (~730 hours). Full simulation parameters are listed in Table 1.

Table 1. Simulation parameters.

Parameter	Value
Network type	LTE / 5G
Number of cells	1,000
Observation period	1 month (~730 h)
Failure distribution	Exponential random burst failures
Repair distribution	Log-normal ($\mu = 2$ h, $\sigma = 1$ h)
Replications	50 Monte-Carlo runs

Each cell's failure process was modeled as a Poisson arrival stream with rate $\lambda = 0.002 \text{ h}^{-1}$, producing exponentially distributed inter-failure intervals. Repair durations were drawn from a log-normal distribution with $\mu = 2$ h and $\sigma = 1$ h to represent the skewed tail of field-maintenance times documented in empirical studies [6], [12]. Spatial burst events were injected at 0.1 events per 730-hour window; each event disabled a Poisson-distributed number of geographically proximate

cells with mean 10, following the clustering behavior documented by Li et al. [13].

At the end of each of the 50 replications, NUR was computed by all five formulations using the same underlying failure/repair trace. This controlled design ensures that differences among model outputs reflect structural modeling choices rather than stochastic variability. Hobler et al. [14] used a comparable replication strategy when evaluating URLLC availability metrics, validating 50 runs as sufficient for stable mean estimation at NUR levels of interest. Within the Monte-Carlo framework, the ground-truth unavailability is defined directly from the generated failure/repair trace as:

$$U_{true} = (\sum_i \sum_j dij) / (N \cdot T) \quad (8)$$

where dij is the j -th outage duration of cell i , N is the number of cells ($N = 1,000$), and T is the observation window ($T = 730$ hours). All reported deviations are measured against U_{true} ($NUR_{true} = 0.0035$), not against the cell-based estimator. This makes the benchmark independent of any of the five candidate formulations.

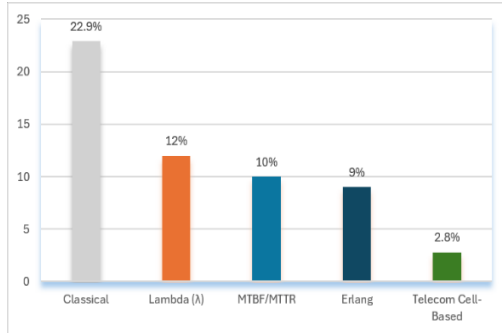


Figure 1. Example failure/repair timeline for a single cell over the 730-hour window.

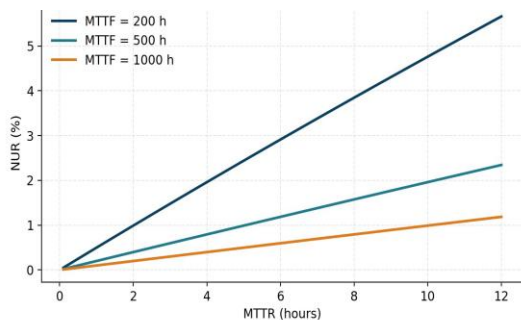


Figure 2. Distribution of per-cell unavailability rates across the 1,000-cell topology.

9. Results and Discussion

Mean NUR values and confidence intervals from the 50 replications are summarized in Tables 2 and 3. Measured against the empirical simulation ground truth ($NUR_{true} = 0.0035$), the classical model produced $NUR = 0.0027$, underestimating the actual network unavailability by approximately 22.9% due to spatial aggregation that smoothes out localized cell-outage clusters. The cell-based telecom model achieved the highest precision ($NUR = 0.00341$, representing a deviation of only -2.8%) as it retains cell-granular failure counters without network-wide spatial averaging. The MTBF/MTTR, λ , and Erlang queuing models occupied intermediate deviation bands of -10.0%, -12.0%, and -9.0%, respectively.

Table 2. Computed NUR for the classical and telecom models.

Model	Computed NUR	Relative Deviation
Classical model	0.0027	-22.9%
Telecom model	0.0035	-2.8%

Table 3. Comparison of NUR computation models.

Model	Formula Basis	Spatial	Mean Deviation (%)
Classical	Uptime ratio	No	-22.9%
Lambda (λ)	Failure rate	No	-12.0%
MTBF/MTTR	Reliability	Partial	-10.0%
Erlang	Traffic	Partial	-9.0%
Telecom Cell-Based	Cell KPIs	Yes*	-2.8%

The gap between the classical model and the cell-based result originates primarily from burst-failure episodes. When spatial events are introduced, the cell-based model records higher $T_{down,i}$ values for each affected site. The classical formulation relies on network-wide averaging, so the impact of outages affecting specific cells is diminished in the reported availability. Emara et al. [15] had already noted this effect, showing that aggregate availability measures often overlook spatially correlated failures even though they significantly degrade service at the local level. Table 4 illustrates how NUR responds to changes in MTTR when λ is fixed. Doubling MTTR leads to a proportional doubling of NUR in both models, reflecting the linear dependence on repair duration

under exponential failure assumptions. At higher MTTR values, however, the gap between the two models grows: the cell-based approach weighs long repairs more heavily, since each affected cell contributes its full outage fraction rather than being offset by neighboring cells that remain online.

Table 4. Sensitivity of NUR to MTTR variation.

MTTR (h)	NUR (classical)	NUR (cell-based)
1	0.0014	0.0018
2	0.0027	0.0035
4	0.0054	0.0071
8	0.0108	0.0143

The Erlang model provides intermediate accuracy: it improves on the λ formulation but falls short of the cell-based approach. A key contribution of the Erlang approach is that it incorporates queuing effects in repair crews, thereby reflecting how limited availability can stretch MTTR beyond the nominal repair time. Eklundh [8] showed that blocking probability increases sharply once traffic exceeds about 80% of crew capacity, and the simulations here operated in that range, producing noticeable queuing effects. Kogan and Tarapore [19] likewise observed that saturated repair queues are a major factor in MTBO degradation in real telecom networks.

Data from large-scale campaigns [13] and supporting field studies [12] point to significant spatial differences in how cell-failure rates are distributed. This evidence suggests that models which ignore spatial structure—such as the classical and λ formulations—tend to underestimate actual network unavailability. Reliability-based formulations address MTTR, but they remain unable to represent burst failures that spread through correlated clusters [8], [19].

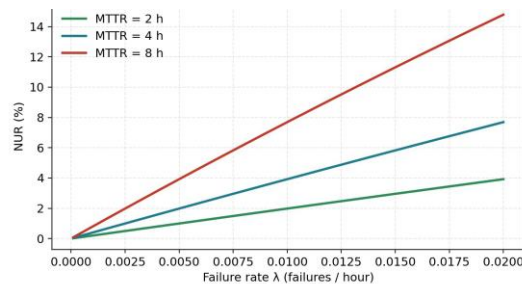


Figure 3. Mean NUR versus MTTR for all five formulations (λ held constant).

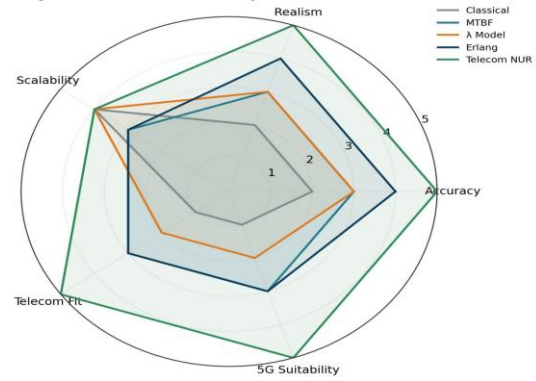


Figure 4. Box plots of NUR over 50 replications for each model.

From a practical standpoint, the choice of NUR model carries direct consequences for SLA compliance assessment. An operator relying on the classical ratio model may report 99.73% availability while the cell-based equivalent reveals 99.65% — a gap that, despite being small in absolute terms, corresponds to approximately 52 extra minutes of annual customer-perceived downtime per cell. At the scale of thousands of cells, this discrepancy translates into material SLA penalty exposure. Turkka and Foo [16] raised the same concern in their standardization proposal for 5G service availability metrics.

Vendor NMS platforms and OSS architectures increasingly support cell-granular KPI pipelines [7], [9] that make the cell-based computation operationally feasible without additional instrumentation. Cho et al. [4] demonstrated that AI-based diagnostic tools can identify anomalous cells automatically, easing the burden of manually locating burst-failure clusters. With current OSS platforms already supporting cell-level KPI pipelines, the cell-based NUR model is not only analytically sound but also feasible to implement in practice. With an eye to the future, studies by researchers such as Ijaz et al. [21] and Li et al. [20] highlight the value of proactive reliability prediction, especially in high-mobility 5G contexts, as a key direction for subsequent research.

precluded by the synthetic nature of our envelope, the structural direction of these findings is qualitatively consistent with empirical field measurements reported by Li et al. [13] and Baltrunas et al. [12]. Both studies observed that coarse, spatio-temporally aggregated metrics systematically underestimate localized, bursty

outage events in cellular deployments. Our simulation results mirror this real-world phenomenon: spatially aggregated formulations (e.g., the classical model at -22.9%) dilute geographically concentrated downtime, whereas cell-resolved tracking retains local outage severity.

Limitations. Three specific limitations bound these findings. (i) The benchmark is synthetic; validation against live operator OSS traces was not possible and remains necessary before these deviation magnitudes can be generalized across diverse operational networks. (ii) The reported numerical deviations hold strictly for the tested parameter envelope ($\lambda = 0.002 \text{ h}^{-1}$, log-normal repair times with $\mu = 2 \text{ h}$ and $\sigma = 1 \text{ h}$, and a spatial burst rate of 0.1 per 730 h) and are not claimed to be universally constant. (iii) Spatially correlated failures are represented solely through injected burst events; explicit spatial-dependence and spatial-correlation models [15], [17] are left to future work.

10. Conclusions

We examined five different NUR formulations by applying a unified analytical-simulation framework to LTE/5G networks. The evaluation covered 1,000 cells and was repeated over 50 Monte-Carlo replications against an independent event-log ground truth (NUR_{true} = 0.0035). The results establish a clear performance hierarchy: the classical model underestimates real downtime by $\sim 22.9\%$, the λ and MTBF/MTTR models achieve $\sim 12.0\%$ and $\sim 10.0\%$ deviation respectively, the Erlang queuing model reaches $\sim 9.0\%$, and the telecom cell-based model yields the highest precision with a deviation of only $\sim 2.8\%$.

The advantage of the cell-based formulation stems from its preservation of per-cell resolution: when correlated burst failures concentrate downtime in a subset of cells, cell-level aggregation retains that concentration instead of diluting it across the network. We emphasise that Equation (7) is not a spatially-aware model in the sense of Emara et al. [15]: it contains no geographic, adjacency, or correlation term. Its sensitivity to burst events is a consequence of resolution, not of explicit spatial or cascading failure modelling. As 5G URLLC requirements [14] and high-mobility deployments [20] push

availability targets toward six nines and beyond, aggregate metrics become insufficient for SLA verification and fault localization. The telecom cell-based NUR model is therefore recommended as a practical operational standard for performance monitoring and SLA compliance assessment in 5G and next-generation networks.

Declarations and Supplementary Material

As a former Team Leader at Iraqna Company for Mobile, the author sought operational data from telecommunications providers in Iraq but was unable to obtain it owing to corporate confidentiality restrictions. Monte-Carlo simulation was consequently employed to generate the dataset used in this study.

Abbreviations

Abbreviation	Full Form
5G	Fifth Generation
BTS	Base Transceiver Station
eNB	Evolved Node B
ETSI	European Telecommunications Standards Institute
ITU	International Telecommunication Union
KPI	Key Performance Indicator
LTE	Long-Term Evolution
MTBF	Mean Time Between Failures
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
NMS	Network Management System
NUR	Network Unavailability Rate
OSS	Operations Support System
QoS	Quality of Service
RAN	Radio Access Network
SLA	Service Level Agreement
URLLC	Ultra-Reliable Low-Latency Communications

Conflict of Interest

The authors declare no conflict of interest with respect to this research.

Funding

No external funding was received for conducting this study.

Author Contribution

The authors conceived the research question, carried out all analytical derivations, designed and

executed the Monte-Carlo simulation, interpreted the results, and prepared the manuscript.

AI Declaration Statement

The author confirms that no generative AI or AI-assisted writing tool was used in preparing this manuscript.

References

- [1] P. Cholda, J. Tapolcai, T. Cinkler, K. Wajda, and A. Jajszczyk, "Quality of resilience as a network reliability characterization tool," *IEEE Netw.*, vol. 23, no. 2, pp. 11–19, Mar./Apr. 2009. <https://doi.org/10.1109/MNET.2009.4804331>
- [2] V. Netes, "Modern network technologies and dependability," in *Proc. IEEE MONETEC*, 2020, pp. 1–5. <https://doi.org/10.1109/MONETEC49726.2020.9258328>
- [3] M. Al-Kuwaiti, N. Kyriakopoulos, and S. Hussein, "A comparative analysis of network dependability, fault-tolerance, reliability, security, and survivability," *IEEE Commun. Surveys Tuts.*, vol. 11, no. 2, pp. 106–124, 2009. <https://doi.org/10.1109/SURV.2009.090208>
- [4] Y.-J. Cho, Y. S. Kim, S. Kim, D. Sim, and D.-Y. Kwak, "AI-enabled wireless KPI monitoring and diagnosis system for 5G cellular networks," in *Proc. IEEE ICTC*, Jeju, South Korea, Oct. 2019, pp. 1115–1117. <https://doi.org/10.1109/ICTC46691.2019.8939988>
- [5] P. Snow, U. Varshney, and A. D. Malloy, "Reliability and survivability of wireless and mobile networks," *Computer*, vol. 33, no. 7, pp. 49–55, Jul. 2000. <https://doi.org/10.1109/2.869370>
- [6] R. Bothwell, R. Donthamsetty, Z. Kania, and R. Wesoloski, "Reliability evaluation: A field experience from Motorola's cellular base transceiver systems," in *Proc. IEEE RAMS*, Las Vegas, NV, USA, Jan. 1996, pp. 1–6. <https://doi.org/10.1109/RAMS.1996.500685>
- [7] T.-H. Wang, Y.-C. Chen, S.-J. Huang, K.-S. Hsu, and C.-H. Hu, "Design of a network management system for 5G open RAN," in *Proc. IEEE APNOMS*, Tainan, Taiwan, Sep. 2021, pp. 1–4. <https://doi.org/10.23919/APNOMS52696.2021.9562627>
- [8] B. Eklundh, "Channel utilization and blocking probability in a cellular mobile telephone system with directed retry," *IEEE Trans. Commun.*, vol. 34, no. 4, pp. 329–337, Apr. 1986. <https://doi.org/10.1109/TCOM.1986.1096544>
- [9] R. Lazar, A. V. Militaru, C. Caruntu, C. Pascal, and C. Patachia-Sultanoiu, "Real-time data measurement methodology to evaluate the 5G network performance indicators," *IEEE Access*, vol. 11, pp. 44312–44326, 2023. <https://doi.org/10.1109/ACCESS.2023.3271366>
- [10] G. Caso, M. Rajiullah, A. Brunstrom, L. De Nardis, and O. Alay, "A standardized evaluation of QoS/QoE performance in 5G and beyond-5G systems," *IEEE Commun. Standards Mag.*, 2025. <https://doi.org/10.1109/MCOMSTD.2025.3622065>
- [11] H. Farooq, M. S. Parwez, and A. Imran, "Continuous time Markov chain based reliability analysis for future cellular networks," in *Proc. IEEE GLOBECOM*, San Diego, CA, USA, Dec. 2015, pp. 1–6. <https://doi.org/10.1109/GLOCOM.2015.7417594>
- [12] D. Baltrunas, A. Elmokashfi, and A. Kvalbein, "Measuring the reliability of mobile broadband networks," in *Proc. ACM IMC*, Vancouver, BC, Canada, Nov. 2014, pp. 45–58. <https://doi.org/10.1145/2663716.2663725>
- [13] Y. Li, H. Lin, Z. Li, Y. Liu, and F. Qian, "A nationwide study on cellular reliability: Measurement, analysis, and enhancements," in *Proc. ACM SIGCOMM*, Virtual, Aug. 2021, pp. 336–349. <https://doi.org/10.1145/3452296.3472908>

-
- [14] T. Hobler, M. Simsek, and G. Fettweis, "Joint analysis of channel availability and time-based reliability metrics for wireless URLLC," in *Proc. IEEE GLOBECOM*, Abu Dhabi, UAE, Dec. 2018, pp. 1–6. <https://doi.org/10.1109/GLOCOM.2018.8647801>
- [15] M. Emara, M. C. Filippou, and I. Karls, "Availability and reliability of wireless links in 5G systems: A space-time approach," in *Proc. IEEE GLOBECOM Workshops*, Abu Dhabi, UAE, Dec. 2018, pp. 1–7. <https://doi.org/10.1109/GLOCOMW.2018.644278>
- [16] J. Turkka and S. Y. Foo, "Measuring communication service availability for 5G networks," in *Proc. IEEE ICECCME*, Maldives, Nov. 2022, pp. 1–6. <https://doi.org/10.1109/ICECCME55909.2022.9987830>
- [17] H. Kaja, R. A. Paropkari, C. Beard, and J. Minden, "Survivability and disaster recovery modeling of cellular networks using matrix exponential distributions," *IEEE Trans. Netw. Service Manag.*, vol. 18, no. 3, pp. 2947–2962, Sep. 2021. <https://doi.org/10.1109/TNSM.2021.3090355>
- [18] Gautam and S. Dharmaraja, "Reliability and survivability assessment of LTE-A architecture and networks," *Opsearch*, vol. 60, no. 1, pp. 1–22, Jan. 2023. <https://doi.org/10.1007/s12597-022-00607-y>
- [19] Y. Kogan and P. Tarapore, "MTBO—A metric for assessing production failure rates in telecommunications networks," in *Proc. IEEE BCFIC*, Raleigh, NC, USA, Apr. 2012, pp. 1–5. <https://doi.org/10.1109/BCFIC.2012.6217978>
- [20] R. Li, B. Decocq, A. Barros, and Y. Fang, "High-mobility 5G communication service: Availability and reliability analysis," in *Proc. IEEE ICSRS*, Athens, Greece, Nov. 2023, pp. 1–7. <https://doi.org/10.1109/ICSRS59833.2023.10381382>
- [21] Ijaz, W. Raza, S. Riaz, and A. Imran, "On multi-parameter optimization and proactive reliability in 5G and beyond cellular networks," *Sensors*, vol. 25, no. 24, p. 7651, Dec. 2025. <https://doi.org/10.3390/s25247651>
-



Reservoir Porosity Prediction in the Koroshina Dolomite Formation, Sadad Gas Field, Syria, Using Seismic Inversion and Artificial Neural Networks

Wasim Ali Alrhayel^{1*}

¹ Department of Petroleum Engineering, Homs University, Homs, Syrian Arab Republic.

Article Info	ABSTRACT
Received: 11 Sep. 2026 Revised: 23 Sep. 2026 Accepted: 25 Sep. 2026 Available online: 30 Sep. 2026 Keywords: Sadad Gas Field; Koroshina Dolomite; Seismic Inversion; Porosity Prediction; Probabilistic Neural Network	The Koroshina Dolomite Formation is an important gas-bearing carbonate reservoir in the Sadad Gas Field, central Syria, where strong structural heterogeneity and limited well control make the prediction of reservoir properties challenging. This study aims to predict the spatial distribution of reservoir porosity within the Koroshina Dolomite Formation by integrating well-log data, two-dimensional (2D) post-stack seismic data, seismic inversion, and artificial neural network modeling. Well-log data from the SADAD-1 and SADAD-2 wells were integrated with a migrated 2D seismic profile crossing both wells. Model-based post-stack seismic inversion was performed using Hampson–Russell software to obtain an acoustic impedance model constrained by well-log data. Seismic attributes derived from the inversion results were then analyzed and used as input variables for a Probabilistic Neural Network (PNN), with measured well-log porosity used as the target property. Porosity prediction using individual seismic attributes produced a correlation coefficient of approximately 39.7%, which increased to 75.1% when 28 seismic attributes were combined. The final PNN model achieved a correlation coefficient of approximately 83.5% between predicted and measured porosity. The resulting porosity model revealed pronounced lateral and vertical heterogeneity within the reservoir. Higher predicted porosity near the SADAD-2 well and the associated reverse-fault zone is interpreted as fracture-related secondary porosity, whereas lower-porosity areas are associated with compaction and cementation. These results demonstrate that integrating post-stack seismic inversion, seismic attributes, and PNN modeling can provide a practical approach for extending porosity prediction into interwell areas and improving characterization of structurally complex carbonate reservoirs.

1. Introduction

The structural complexity of the Sadad area, particularly the presence of reverse faults and fracture systems, can affect the continuity and thickness of the Koroshina Dolomite reservoir and contribute to lateral variations in reservoir

properties. This structural complexity is supported by the well data, particularly from SADAD-2, where a reverse fault has resulted in the repetition of part of the Koroshina Dolomite interval. The well-top data further indicate variations in the thickness of the investigated interval between SADAD-1 and SADAD-2, reflecting the structural complexity of the study area. These geological

variations can increase the uncertainty associated with predicting reservoir properties between wells [1–3,6].

Carbonate reservoirs host a substantial proportion of the world's hydrocarbon resources; however, they are among the most challenging reservoir systems to characterize because of their pronounced heterogeneity. This heterogeneity is controlled by variations in depositional environments, diagenetic processes, and tectonic deformation, which can significantly affect the distribution and quality of reservoir properties. In particular, porosity and permeability may vary considerably both vertically and laterally, making accurate characterization and prediction of reservoir properties essential for effective reservoir evaluation and development [11–16]. In this geological context, the Sadad Gas Field, located in the western part of the Dou Basin, represents one of the important gas discoveries in central Syria. Although several exploration wells have been drilled in the field, well control remains relatively sparse over large areas. Furthermore, geological investigations indicate that structural deformation has significantly influenced reservoir continuity. In particular, the SADAD-2 well intersected a major reverse fault that repeated part of the Koroshina Dolomite Formation and affected reservoir continuity. This structural complexity contributed to the non-productive nature of the well despite the occurrence of fractured intervals [3–5,10].

Conventional petrophysical evaluation provides direct and reliable measurements of reservoir properties at well locations; however, it cannot adequately describe their spatial variation away from the wells. This limitation becomes particularly important in fields such as Sadad, where well control is relatively sparse and structural deformation affects reservoir continuity. In recent years, seismic inversion has become an effective technique for transforming seismic reflection data into acoustic impedance models that can be quantitatively related to reservoir properties. When integrated with seismic attribute analysis, seismic inversion can provide spatial information between wells and improve the characterization of heterogeneous reservoirs [11–17].

Machine-learning techniques can further enhance the relationship between seismic-derived

information and well-log measurements. Among the available machine-learning methods, the Probabilistic Neural Network (PNN) has demonstrated the ability to model nonlinear relationships between seismic attributes and well-log data. Previous studies have applied PNN-based approaches to the prediction of reservoir properties, including porosity, permeability, and fluid-related parameters, demonstrating its potential for estimating petrophysical properties from seismic information [16,18]. Therefore, combining seismic inversion with PNN modelling provides a potential approach for extending well-derived reservoir information into areas where direct well measurements are unavailable.

Recent studies have further demonstrated the effectiveness of integrating seismic attributes and machine-learning techniques for reservoir characterization and porosity prediction. Topór and Sowizdżał [19] applied machine-learning ensemble methods to multiple seismic attributes for porosity prediction in a carbonate reservoir and evaluated several machine-learning models for this purpose [19].

Sotelo et al. [20] applied probabilistic neural networks (PNN) and deep feedforward neural networks to post-stack seismic inversion using multiple seismic attributes, and compared their results with model-based inversion. The study generated porosity volumes and reported reliable PNN prediction when compared with well-log data [20].

Hosseinzadeh et al. [21] reviewed a range of seismic inversion approaches for reservoir characterization, including post-stack methods such as model-based inversion and machine-learning-based approaches, emphasizing the role of seismic inversion in converting seismic reflection data into quantitative reservoir properties [21].

Although previous studies have demonstrated the effectiveness of seismic inversion, seismic attributes, and artificial neural networks for reservoir characterization and porosity prediction, most of these studies have focused on other geological settings and datasets. In particular, limited studies have investigated the integration of post-stack 2D seismic inversion with well-log data and a Probabilistic Neural Network (PNN) for porosity prediction in the Koroshina Dolomite Formation of the Sadad Gas

Field, Syria. Furthermore, the relationship between acoustic impedance derived from seismic inversion and well-log-derived porosity has not been sufficiently investigated in this field. Therefore, a research gap remains in developing and evaluating a field-specific workflow for predicting reservoir porosity in undrilled areas of the Sadad Gas Field. This study addresses this gap by integrating well-log data, 2D post-stack seismic inversion, seismic attributes, and a PNN to estimate reservoir porosity and extend the available well information into undrilled areas.

Building on this identified research gap, the originality of the present study lies in the field-specific integration of post-stack 2D seismic inversion, seismic attributes, well-log data, and a Probabilistic Neural Network (PNN) for porosity prediction in the Koroshina Dolomite Formation of the Sadad Gas Field. Rather than proposing a new inversion or machine-learning algorithm, this study focuses on the application and evaluation of an integrated workflow under the specific geological conditions of the Sadad Gas Field, where limited well control and fault-related reservoir heterogeneity present significant challenges for porosity prediction. The study further evaluates the relationship between seismic-derived acoustic impedance and well-log-derived porosity and applies the integrated results to extend porosity estimation from existing wells into undrilled areas. This field-specific application provides a practical contribution to reservoir characterization and porosity prediction in a structurally complex carbonate reservoir.

To address this research gap, the present study integrates post-stack 2D seismic inversion, acoustic impedance modelling, seismic attribute analysis, and Probabilistic Neural Network (PNN) modelling to predict the spatial distribution of porosity within the Koroshina Dolomite Formation in the Sadad Gas Field. The integration of well-log data with seismic-derived attributes provides a field-specific workflow for extending porosity estimation into undrilled areas and for evaluating the influence of structural heterogeneity on reservoir properties. The results are intended to improve reservoir characterization and provide additional information for future exploration and field development in the Sadad Gas Field.

The Sadad Gas Field is located within the Daw Basin in central Syria, which forms part of the Palmyride tectonic province. The basin is characterized by a thick sedimentary succession ranging in age from the Paleozoic to the Cenozoic and has undergone several tectonic phases that significantly influenced its structural evolution and hydrocarbon accumulation. Compressional tectonic events associated with the development of the Palmyride Fold Belt generated numerous folds and reverse faults that controlled the geometry of the hydrocarbon traps and the distribution of reservoir properties [1,2].

The main reservoir investigated in this study is the Koroshina Dolomite Formation, which belongs to the Upper Triassic succession and represents one of the most productive carbonate reservoirs in the Daw Basin. The formation consists predominantly of crystalline and fractured dolomite with subordinate limestone, shale, and anhydrite interbeds. Owing to its favorable reservoir characteristics, the Koroshina Dolomite Formation constitutes the principal gas-bearing interval in the Sadad Gas Field and several neighboring hydrocarbon fields [2,6–8].

According to the reservoir subdivision adopted by the Syrian Petroleum Company, the Koroshina Dolomite Formation is divided into three main reservoir units (C2, D1, and D2). These units exhibit noticeable variations in reservoir quality resulting from changes in depositional facies, diagenetic processes, and structural deformation. Secondary porosity associated with dolomitization and tectonic fracturing plays a major role in enhancing the storage capacity of the reservoir, whereas cementation locally reduces porosity and permeability [1,2,6].

Geological correlation between the drilled wells indicates that the Koroshina Dolomite Formation maintains relatively consistent stratigraphic thickness throughout the study area. However, structural deformation caused by reverse faulting locally offsets the reservoir succession and affects lateral continuity. These structural features have a direct influence on hydrocarbon migration, reservoir compartmentalization, and the spatial distribution of petrophysical properties [1,3–5,10].

The structural framework of the field indicates that reverse faulting represents the dominant tectonic element controlling reservoir

architecture. These faults not only displace the reservoir units but also generate fracture systems that locally enhance secondary porosity. Nevertheless, fracture-related porosity does not necessarily improve reservoir performance unless adequate permeability and hydraulic connectivity are maintained. Therefore, understanding the geological and structural framework is fundamental for interpreting porosity distribution and evaluating reservoir quality within the Koroshina Dolomite Formation [3,6,10].

2. Research Methodology

The workflow adopted in this study integrates post-stack seismic inversion with seismic attribute analysis and Probabilistic Neural Network (PNN) modeling to predict the spatial distribution of porosity within the Koroshina Dolomite Formation. The methodology consists of four successive stages: (1) well-to-seismic calibration, (2) model-based post-stack seismic

inversion, (3) seismic attribute extraction, and (4) porosity prediction using the PNN algorithm.

Initially, the available well-log data from the SADAD-1 and SADAD-2 wells were edited and quality controlled. Compressional sonic (DT) and bulk-density (RHOB) logs were used to calculate acoustic impedance (AI), while neutron-porosity (NPHI) data were used to obtain the measured porosity values for the subsequent porosity analysis. The interpreted formation tops were used to establish the relationship between the geological horizons and the seismic reflections and to define the stratigraphic interval investigated in the inversion

The interpreted seismic section used in this study is shown in Fig. 1. The section crosses both SADAD-1 and SADAD-2 and images the Koroshina Dolomite reservoir, providing the seismic framework required for acoustic impedance inversion and subsequent reservoir property prediction.

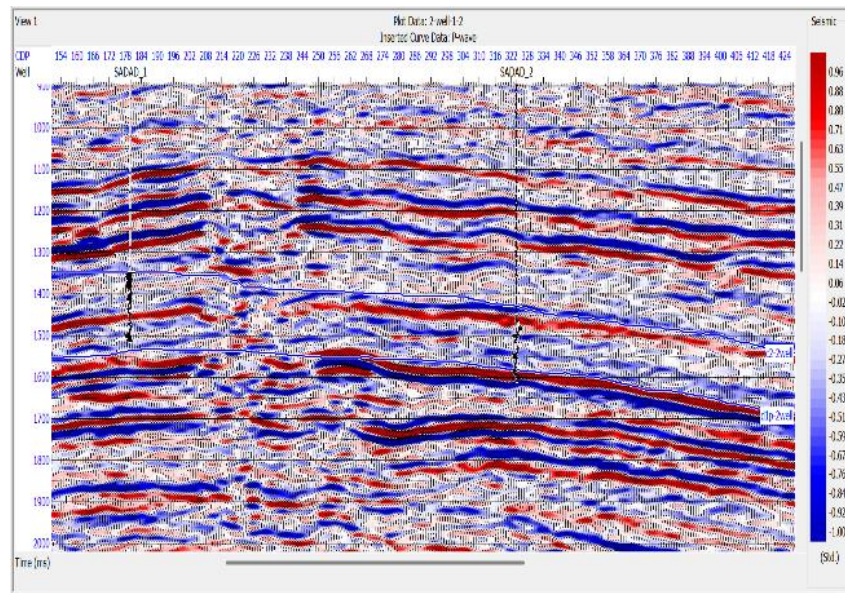


Figure 1. Interpreted 2D seismic section crossing the SADAD-1 and SADAD-2 wells (after Ref. [1]).

2.1. Study Area and Dataset

This study was carried out using an integrated dataset comprising well-log data from two wells, SADAD-1 and SADAD-2, together with one two-dimensional (2D) post-stack seismic line acquired over the Sadad Gas Field. The selected seismic line crosses both wells and provides the seismic framework for well-to-seismic calibration, post-stack seismic inversion,

seismic attribute extraction, and porosity prediction between the two wells. The subsurface datasets were provided by the Syrian Petroleum Company and constitute the primary data used in this study [1].

The well-log dataset includes compressional-wave (P-wave) sonic data, bulk-density (RHOB) logs, and neutron-porosity (NPHI) data from the SADAD-1 and SADAD-2 wells. The P-wave and

density logs were used to calculate acoustic impedance and to generate synthetic seismograms for well-to-seismic calibration. The neutron-porosity data were used to obtain the measured porosity values used in the porosity analysis and as the target variable for the Probabilistic Neural Network (PNN). Formation tops (well tops) interpreted from the well data were also incorporated to identify the investigated stratigraphic intervals and to constrain the seismic inversion.

The main formation tops and their measured depths (MD) in the SADAD-1 and SADAD-2 wells are summarized in Table 1.

Table 1. Formation tops used to constrain the post-stack seismic inversion (after Ref. [1]).

Well	Formation	MD
SADAD_1	BUTMA	2662
SADAD_1	K. ANHYDRITE	2808
SADAD_1	K. DOLOMITE(C2)	3347
SADAD_1	K. DOLOMITE(D1)	3664
SADAD_1	K. DOLOMITE(D1P)	3690
SADAD_2	BUTMA	2640
SADAD_2	K. ANHYDRITE	2817
SADAD_2	K. DOLOMITE(C2)	3431
SADAD_2	K. DOLOMITE(D1p)	4198

For SADAD-1, the investigated Koroshina Dolomite interval is bounded by the K. DOLOMITE(C2) and K. DOLOMITE(D1) formation tops at depths of 3347 m and 3664 m, respectively. In SADAD-2, the corresponding formation tops occur at 3431 m and 4198 m, respectively. These formation tops were used to define the stratigraphic framework of the investigated interval and to constrain the inversion process.

The seismic dataset consists of one migrated post-stack 2D seismic profile acquired across the central part of the Sadad structure. The selected seismic line intersects both SADAD-1 and SADAD-2, allowing the well-log information to be integrated with the seismic data and enabling the spatial variation of reservoir properties between the two wells to be investigated. The structural map of the top Koroshina Dolomite Formation showing the locations of the drilled wells is presented in Fig. 2, while the location of the interpreted 2D seismic profile is shown in Fig. 3 [1].

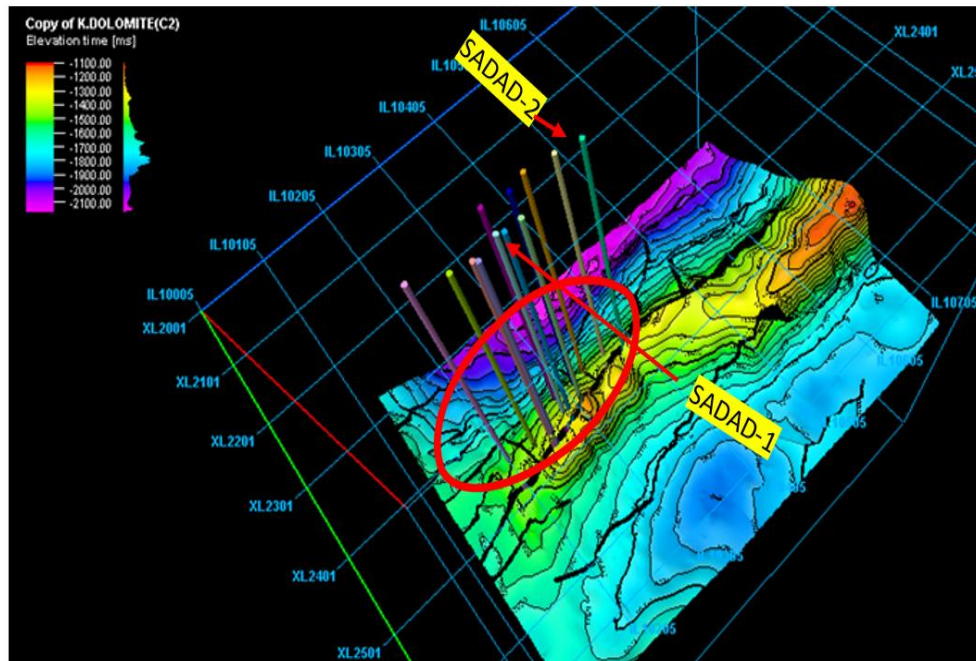


Figure 2. Structural map of the top Koroshina Dolomite Formation showing the distribution of the drilled wells in the Sadad Gas Field (after Ref. [1]).

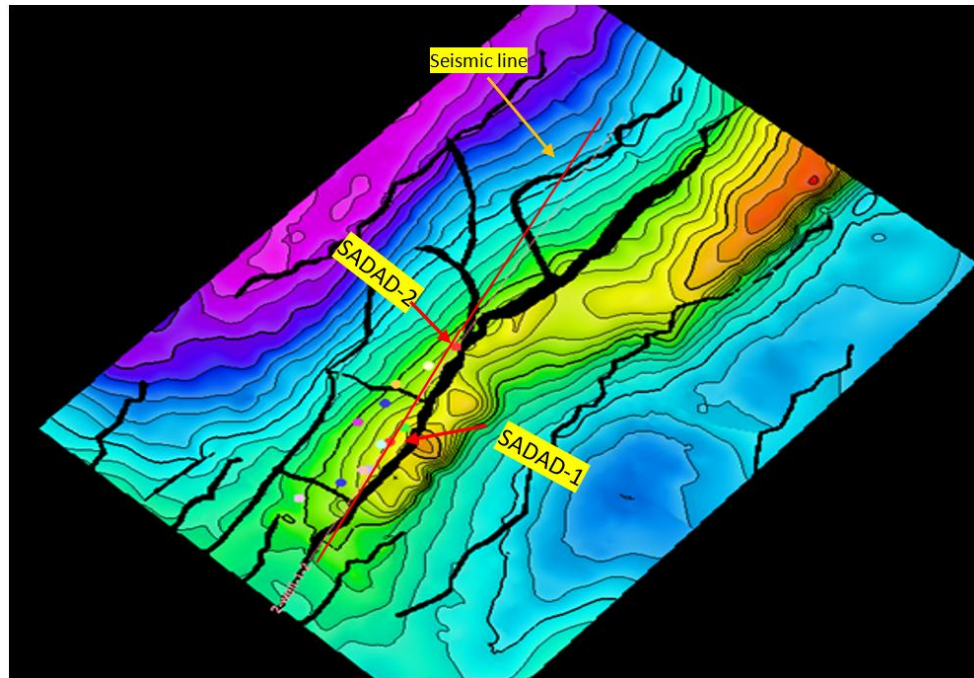


Figure 3. Location of the interpreted 2D seismic line crossing the SADAD-1 and SADAD-2 wells (after Ref. [1]).

The well-log and seismic datasets were integrated through a well-to-seismic tie procedure to establish the time-depth relationship and correlate the seismic reflections with the corresponding geological horizons. The formation tops were used to constrain the investigated interval and the inversion process. The integrated dataset was subsequently used for post-stack seismic inversion, seismic attribute extraction, and porosity prediction using the Probabilistic Neural Network (PNN) workflow [17,18].

2.2. Well-to-Seismic Calibration and Low-Frequency Model Construction.

A synthetic seismogram was generated for each well using the P-wave sonic and density logs and the extracted statistical wavelet. The synthetic and recorded seismic traces were correlated to establish and refine the depth-to-time relationship at the well locations. The well-to-seismic correlation was adjusted to obtain the best correspondence between the synthetic and recorded seismic responses before performing the inversion.

Following the well-to-seismic calibration, a model-based post-stack seismic inversion was performed using the Hampson–Russell software. The initial acoustic impedance model was

constructed from the well-derived acoustic impedance logs and the interpreted formation tops. The impedance logs were interpolated between the available wells using the interpreted horizons to establish the geological framework of the model. A low-pass filter was then applied to the interpolated impedance model to generate the low-frequency background model. The filtering parameters used in the study followed the Hampson–Russell workflow, with frequencies up to 10 Hz passed, frequencies above 15 Hz filtered out, and a gradual transition between these limits. The resulting low-frequency model provided the background impedance trend required for the subsequent model-based inversion.

The formation tops listed in Table 1 were used to constrain the stratigraphic framework and define the interval used for the inversion. The resulting initial model incorporated the low-frequency impedance trend between the wells while preserving the main interpreted geological boundaries.

2.3. Model-Based Post-Stack Seismic Inversion

After construction of the initial low-frequency model, inversion analysis was performed at the well locations to evaluate the inversion parameters and the agreement between

the inverted and well-derived acoustic impedance. The Model-Based inversion method was selected for the final post-stack inversion. The inversion parameters were optimized during the inversion analysis, and the resulting synthetic seismic response was compared with the recorded seismic data to assess the quality of the inversion. The optimized Model-Based inversion was subsequently applied to the interpreted 2D seismic profile to transform the seismic reflection data into an acoustic impedance section. The resulting acoustic impedance model was used as the basis for subsequent seismic attribute extraction and reservoir characterization.

2.4. Seismic Attribute Extraction

The generated acoustic impedance model served as the basis for seismic attribute extraction. Multiple seismic attributes were calculated from the inverted seismic data using the Emerge module of the Hampson–Russell software. These attributes were statistically evaluated to identify those exhibiting the strongest relationship with the measured porosity. Both single-attribute and multi-attribute analyses were performed to assess their predictive capability before applying the machine-learning technique [18].

2.5. Porosity Prediction Using the Probabilistic Neural Network (PNN)

Porosity prediction was performed using the Probabilistic Neural Network (PNN) implemented in the Emerge module of the Hampson–Russell software. The measured porosity values derived from the neutron-porosity (NPHI) logs of the SADAD-1 and SADAD-2 wells were used as the target variable, while seismic attributes extracted from the inverted seismic data were used as input variables [16,18].

The PNN workflow was developed through successive stages. First, individual seismic attributes were evaluated against the measured well-log porosity to investigate their predictive relationships. The initial single-attribute analysis produced a relatively weak correlation coefficient of approximately 39.7%. Subsequently, a multi-attribute analysis was performed using the Emerge module to evaluate the combined contribution of the available seismic attributes. Through iterative

testing, the number of seismic attributes was progressively increased until 28 attributes were reached, providing the highest obtained correlation. Twenty-eight seismic attributes were selected based on their collective relationship with the measured porosity. Their combined use increased the correlation coefficient to approximately 75.1%, compared with 39.7% obtained from the single-attribute analysis. Therefore, the selected twenty-eight attributes were retained as input variables for the subsequent PNN modeling.

while the measured porosity values from the SADAD-1 and SADAD-2 wells were used as the target data. The PNN model was trained using the available well data, and its performance was evaluated by comparing the predicted porosity with the corresponding measured porosity at the available well locations. The final PNN model achieved a correlation coefficient of approximately 83.5% between the predicted and measured porosity values, indicating an improved predictive relationship compared with the preceding single-attribute and multi-attribute analyses.

Following model evaluation, the trained PNN was applied to the complete interpreted 2D seismic section using the selected seismic attributes as input data. The resulting output was a continuous porosity model representing the predicted spatial distribution of porosity within the Koroshina Dolomite Formation between the available well locations and across the investigated seismic section.

3. Results

3.1. Wavelet extraction and well-to-seismic tie

A statistical wavelet was extracted from the seismic data and used to generate synthetic seismograms for well-to-seismic calibration. The extracted wavelet provides the seismic signature required for correlating the well-log responses with the recorded seismic reflections and constitutes an essential input for the post-stack seismic inversion process.

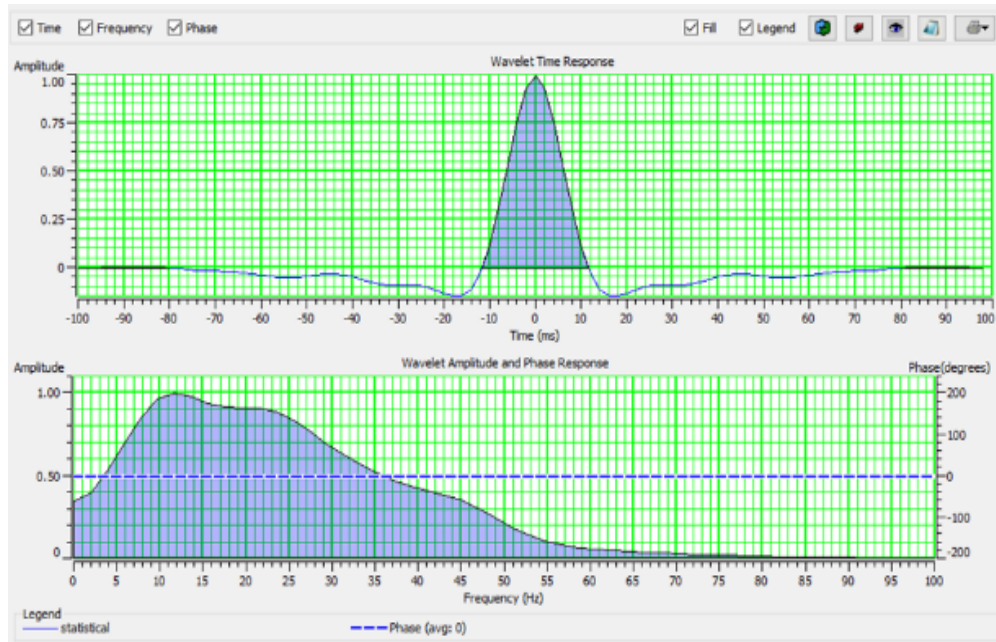


Figure 4. Extracted statistical wavelet used for post-stack seismic inversion.

The synthetic seismograms generated for the SADAD-1 and SADAD-2 wells exhibit excellent agreement with the recorded seismic traces, confirming the accuracy of the time-depth relationship and the reliability of the seismic calibration.

3.2. Post-stack seismic inversion

Following the well-to-seismic calibration, model-based post-stack seismic inversion was performed to estimate the acoustic impedance distribution within the Koroshina Dolomite Formation. Quality-control analysis indicates an excellent match between the inverted acoustic impedance and the well-derived acoustic impedance logs for both wells.

The correlation coefficient between the synthetic and recorded seismic traces reached approximately 99.9%, indicating that the inversion model successfully reproduced the observed seismic response and generated a reliable acoustic impedance model suitable for subsequent reservoir characterization.

The final acoustic impedance section is presented in Fig. 5, illustrating the lateral variation of acoustic impedance across the study area within the Koroshina Dolomite reservoir.

3.3. Porosity prediction using the Probabilistic Neural Network (PNN)

The measured porosity logs from the SADAD-1 and SADAD-2 wells were used as the target data for training the Probabilistic Neural Network (PNN) model. Figure 12 illustrates the input data used during the training process, including the seismic trace, acoustic impedance, and measured porosity.

Initially, porosity prediction was performed using individual seismic attributes. The resulting model produced a relatively weak correlation with the measured porosity, with a prediction accuracy of approximately 39.7%.

Subsequently, twenty-eight seismic attributes were combined to improve the predictive performance. The multi-attribute analysis increased the correlation coefficient to approximately **75.1%**, demonstrating a significant improvement over the single-attribute approach.

The final porosity prediction was carried out using the Probabilistic Neural Network (PNN) trained with the selected seismic attributes. The model achieved the highest prediction accuracy, with a correlation coefficient of approximately 83.5% between the predicted and measured porosity values.

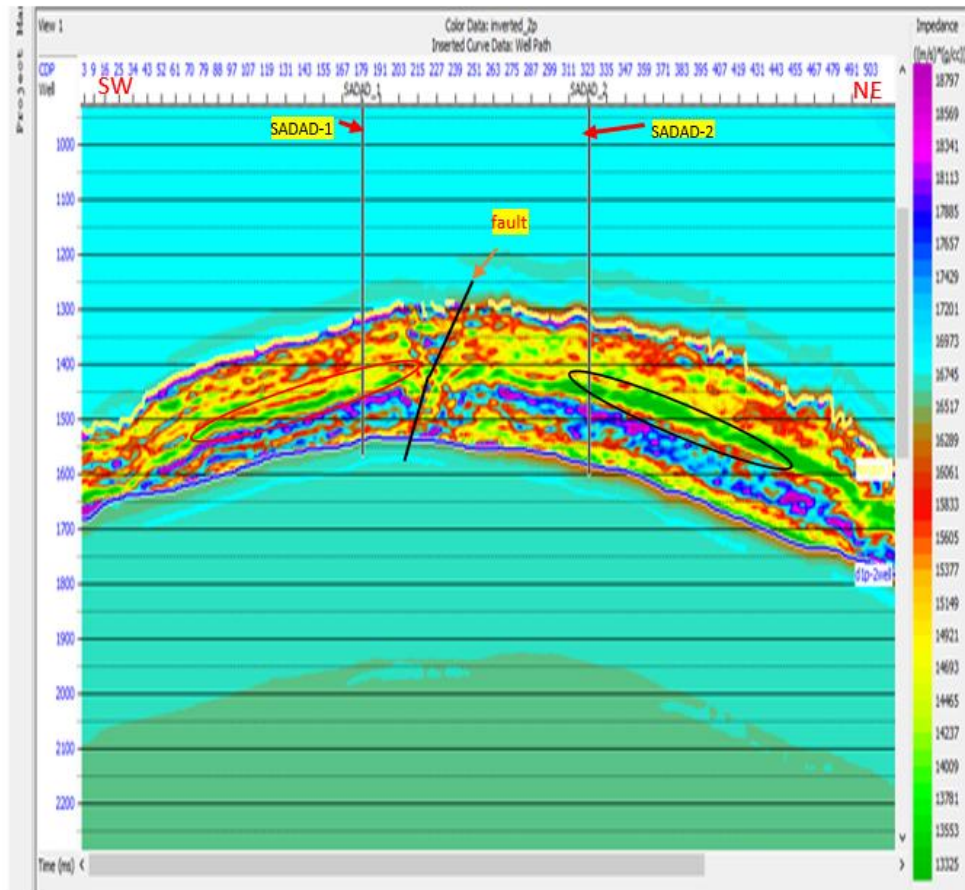


Figure 5. Acoustic impedance section obtained from post-stack seismic inversion.

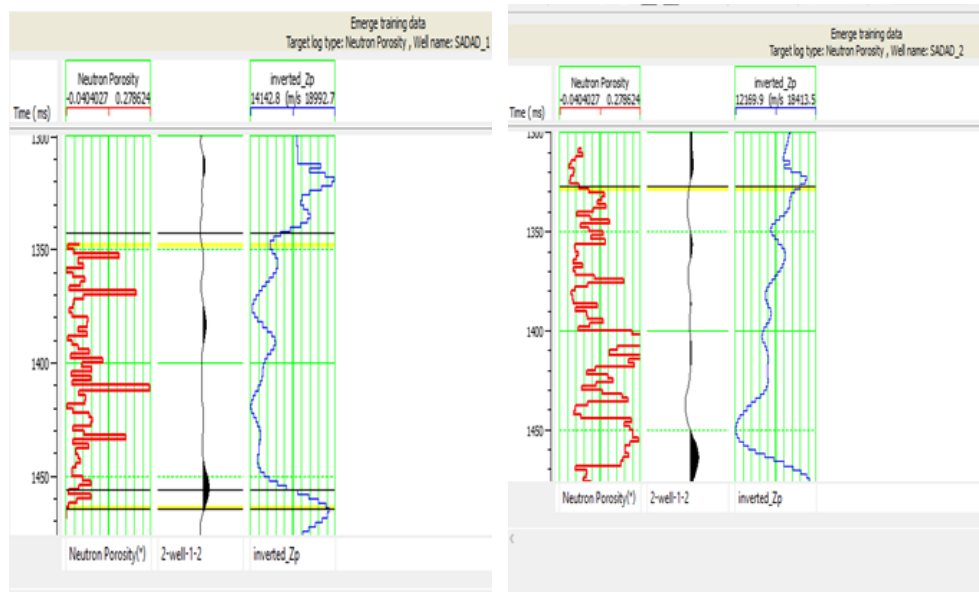


Figure 6. Input data used for PNN training, including seismic trace, acoustic impedance, and measured porosity.

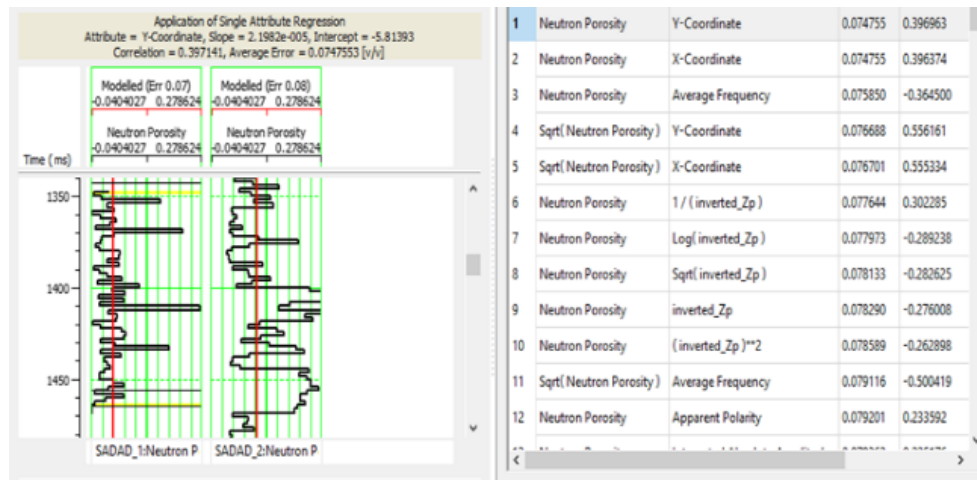


Figure 7. Porosity prediction using individual seismic attributes.

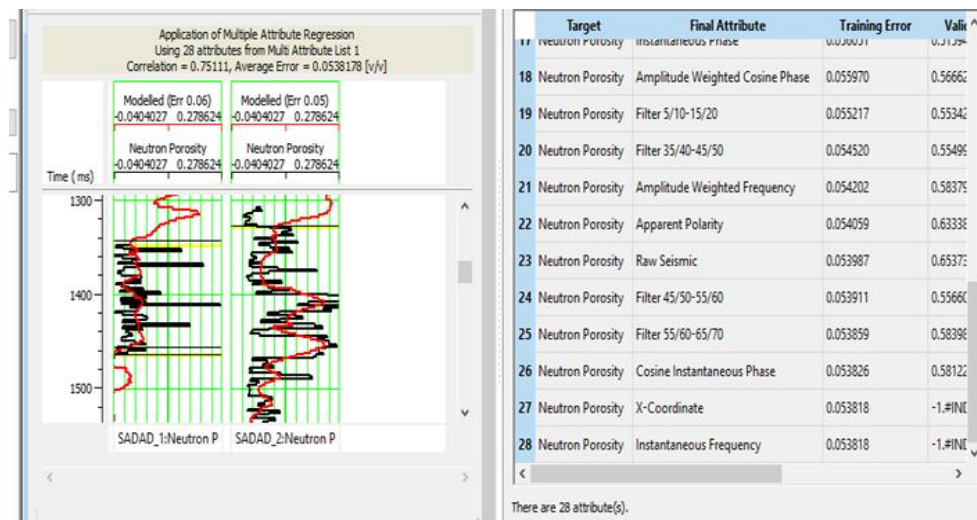


Figure 8. Porosity prediction using twenty-eight seismic attributes.

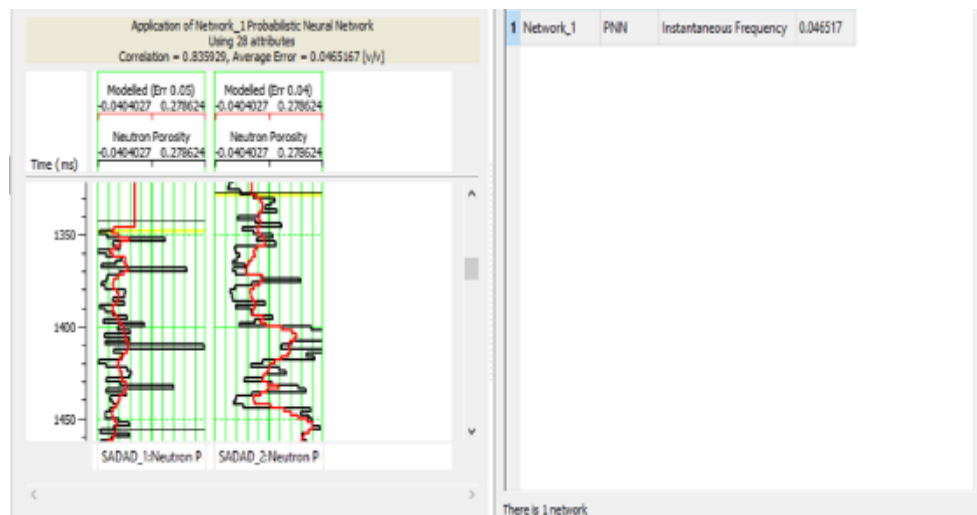


Figure 9. Performance of the Probabilistic Neural Network (PNN) for porosity prediction.

The measured porosity values used during the training process are summarized in Table 2.

Table 2. Measured porosity values from the SADAD-1 and SADAD-2 wells used for PNN training.

SADAD_2	SADAD_1	Porosity
0.29	0.15	High porosity
0.01	0.01	Low porosity

Following model validation, the trained Probabilistic Neural Network (PNN) was applied to the entire interpreted seismic section to predict the spatial distribution of porosity within the Koroshina Dolomite Formation. The resulting porosity model is presented in Fig. 10, where the predicted porosity is displayed as a continuous

color-coded section calibrated with the measured porosity logs from the SADAD-1 and SADAD-2 wells. The close agreement between the projected well-log porosity and the predicted porosity distribution demonstrates the ability of the PNN model to interpolate porosity between wells and extend reservoir property prediction throughout the study area. The blue horizon represents the interpreted top of the Koroshina Dolomite reservoir, defining the geological interval over which the porosity prediction was performed.

The porosity model is calibrated with the measured porosity logs from the SADAD-1 and SADAD-2 wells, while the blue horizon represents the interpreted top of the Koroshina Dolomite reservoir.

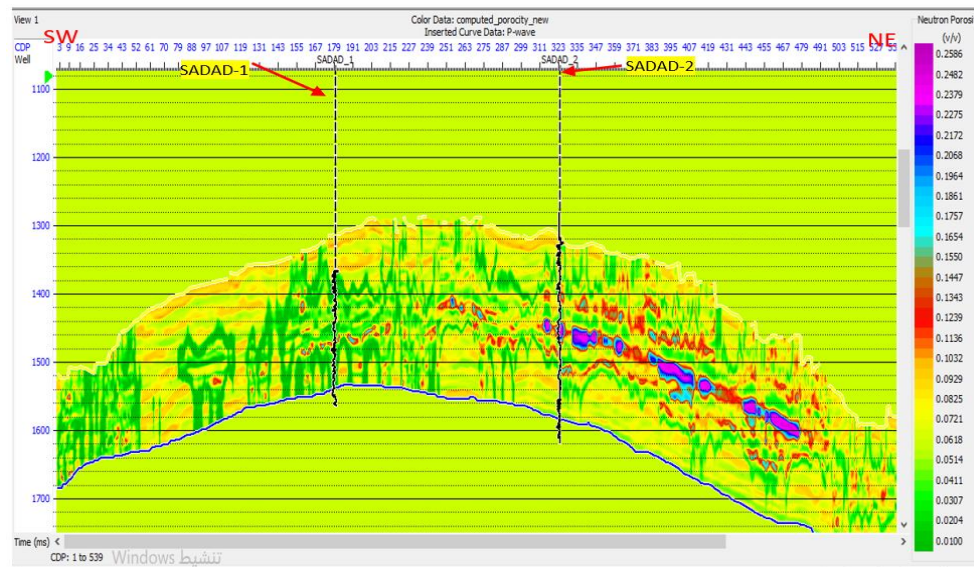


Figure 10. Predicted porosity distribution within the Koroshina Dolomite Formation using the Probabilistic Neural Network (PNN).

4. Discussion

The integration of post-stack seismic inversion with Probabilistic Neural Network (PNN) modeling proved to be an effective workflow for predicting the spatial distribution of porosity within the Koroshina Dolomite Formation. The close agreement between the measured porosity logs and the PNN-predicted porosity section (Fig. 10) demonstrates the capability of the selected seismic attributes to reproduce the spatial variability of reservoir properties beyond the available well control. These results are consistent with previous studies,

which reported that integrating seismic inversion with machine-learning algorithms significantly improves reservoir characterization in heterogeneous carbonate reservoirs [11–16].

The predicted porosity section (Fig. 10) indicates that porosity is not uniformly distributed throughout the Koroshina Dolomite reservoir. Instead, the reservoir exhibits noticeable lateral and vertical heterogeneity, with localized porosity anomalies embedded within intervals of relatively lower porosity. The correspondence between the projected well-log porosity and the predicted porosity distribution confirms the reliability of the trained PNN model and demonstrates its ability to

interpolate porosity between wells while preserving the observed petrophysical trends.

Comparison of the predicted porosity model with the structural interpretation indicates that the distribution of porosity is strongly influenced by the structural framework of the Sadad Gas Field. The structural map (Fig. 11) shows that the interpreted seismic line crosses a major reverse fault affecting the Koroshina Dolomite Formation. Structural deformation associated with this fault is likely responsible for generating fracture systems that contribute to the development of secondary porosity within the reservoir [3,10].

Although fracture-induced porosity increases the available storage space, reservoir productivity depends on additional factors, including permeability, fracture connectivity, and the geomechanical behavior of the reservoir rocks. Variations in geomechanical properties influence fracture propagation, reservoir compartmentalization, and fluid-flow pathways within structurally deformed carbonate reservoirs [9]. Therefore, porosity anomalies identified by the PNN model should be interpreted together with the structural framework to distinguish productive reservoir intervals from fracture-controlled compartments.

Additional evidence is provided by the structural model of the Lower Koroshina Dolomite Formation (Fig. 12) and the detailed interpretation of the reverse fault intersecting the SADAD-2 well (Fig. 13). These structural models demonstrate that the reservoir is compartmentalized by reverse faulting, which significantly influences the continuity of the reservoir units and the distribution of petrophysical properties. The measured neutron-porosity data also show a higher maximum porosity at SADAD-2 (approximately 0.29) compared with SADAD-1 (approximately 0.15). The spatial association between the reverse-fault zone, the structurally disturbed reservoir interval, and the relatively higher measured porosity at SADAD-2 provides geological and petrophysical support for interpreting the relatively high predicted porosity near the fault as potentially related to fracture-associated secondary porosity. However, because direct fracture measurements or detailed core-based fracture characterization are not available in the present dataset, this interpretation should be considered a geological inference rather than direct evidence of fracture-controlled porosity [1,3–5,10].

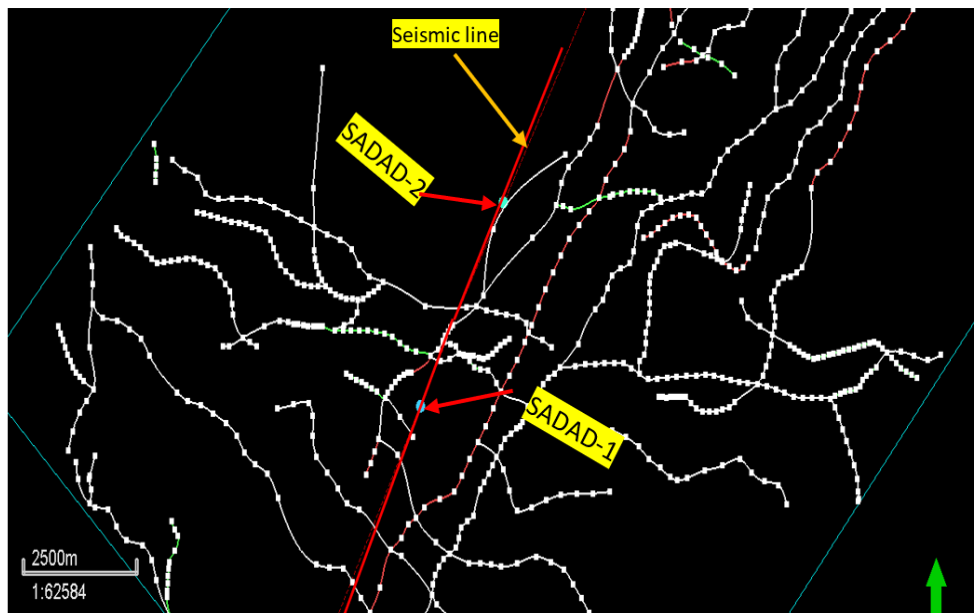


Figure 11. Structural fault map of the Sadad Gas Field showing the location of the interpreted seismic line and drilled wells (after Ref. [10]).

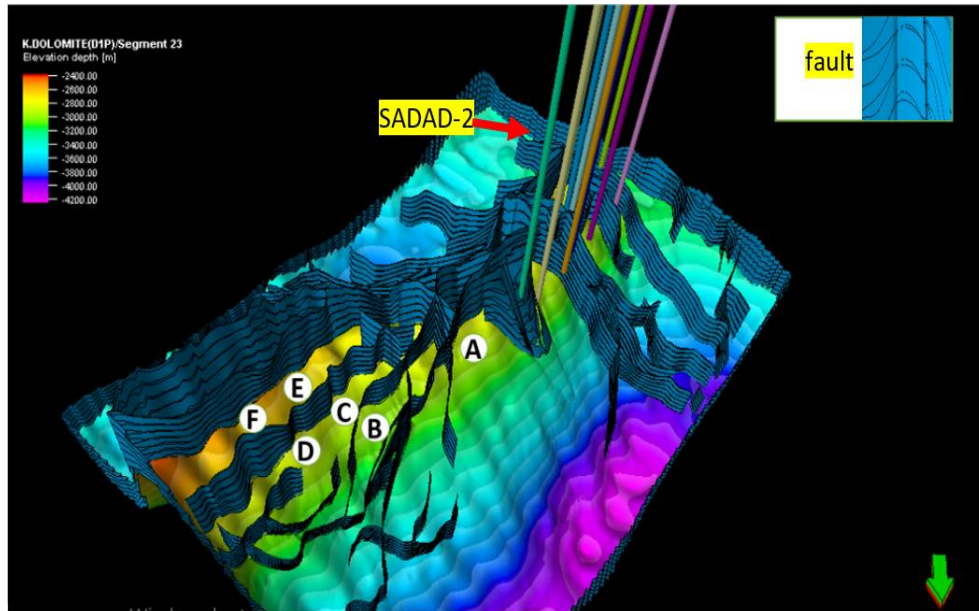


Figure 12. Structural model of the Lower Koroshina Dolomite Formation showing the drilled and proposed well locations (after Ref. [10]).

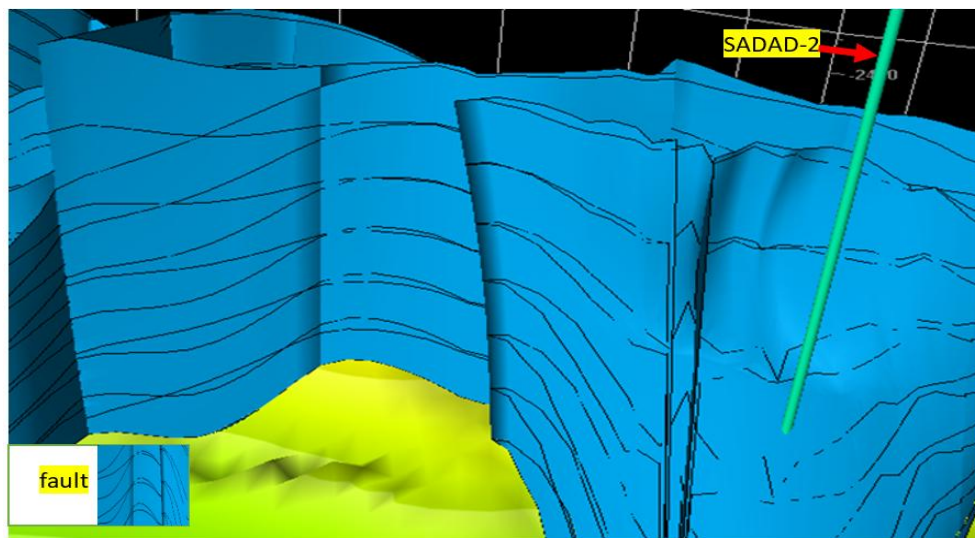


Figure 13. Structural interpretation illustrating the reverse fault intersecting the SADAD-2 well and its influence on reservoir continuity (after Ref. [10]).

The consistency between the acoustic impedance model, the PNN-derived porosity prediction, and the geological interpretation demonstrates the robustness of the proposed workflow. The integration of post-stack seismic inversion, seismic attribute analysis, and Probabilistic Neural Network (PNN) modeling provides a reliable methodology for predicting porosity distribution in carbonate reservoirs with limited well control. The resulting porosity model contributes to reducing geological uncertainty and provides valuable information for future exploration, well placement, and reservoir development in the Sadad Gas Field and similar

structurally complex carbonate reservoirs [15,16,18].

The uncertainty associated with porosity prediction between the SADAD-1 and SADAD-2 wells is mainly related to the limited well control, the heterogeneous nature of the Koroshina Dolomite Formation, and the structural complexity of the study area. The PNN model was trained using porosity data from only two wells, and therefore the predicted porosity between the wells should be considered an interpolation constrained by the available well information rather than a direct measurement. Additional

uncertainty may arise from variations in seismic resolution, the relationship between seismic attributes and porosity, and the presence of reverse faults and fracture-related heterogeneity. Consequently, the predicted porosity anomalies between the wells should be interpreted together with the acoustic impedance model and the geological and structural framework. Additional wells and independent validation data would be required to quantitatively reduce and assess the uncertainty of the predicted porosity distribution.

5. Conclusions

This study demonstrates the effectiveness of integrating post-stack seismic inversion, seismic attribute analysis, and Probabilistic Neural Network (PNN) modeling for predicting the spatial distribution of porosity within the Koroshina Dolomite Formation in the Sadad Gas Field. The proposed workflow successfully combines well-log and seismic data to extend porosity estimation beyond the available well control and improve reservoir characterization.

The main conclusions of this study are summarized as follows:

1. Model-based post-stack seismic inversion generated a reliable acoustic impedance model that showed excellent agreement with the available well-log data, providing a robust foundation for reservoir characterization.
2. The integration of multiple seismic attributes significantly improved porosity prediction compared with the use of individual attributes. The PNN model achieved the highest prediction performance, with a correlation coefficient of approximately 83.5%, demonstrating its capability to model the nonlinear relationship between seismic attributes and porosity.
3. The predicted porosity section revealed that porosity is spatially heterogeneous within the Koroshina Dolomite Formation. The close agreement between the predicted porosity model and the measured porosity logs from the SADAD-1 and SADAD-2 wells confirms the reliability of the proposed workflow for estimating porosity in interwell areas.
4. Integration of the predicted porosity model with the geological and structural interpretation indicates that the spatial

variability of porosity is strongly influenced by structural deformation, particularly reverse faulting, which controlled fracture development, reservoir compartmentalization, and reservoir continuity [1,3–5,10].

5. The consistency between the acoustic impedance model, the predicted porosity distribution, and the geological interpretation confirms the robustness of the proposed methodology for carbonate reservoir characterization under conditions of limited well control.
6. The proposed workflow provides a practical and reliable approach for reservoir evaluation, reducing geological uncertainty, supporting future drilling decisions, and improving reservoir management in the Sadad Gas Field and other structurally complex carbonate reservoirs.

Conflict of interest

The authors declare no conflicts of interest concerning this research.

Funding

No funding was received for conducting this study.

AI Declaration Statement

The authors confirm that the manuscript has been written without the assistance of generative AI or AI-based writing tools.

References

- [1] Syrian Petroleum Company, *Regional Geology Report of the Daw Basin*. Exploration Directorate, Damascus, Syria, 2015, unpublished report.
- [2] A. Mansour, *Integration of Litho-Techno-Seismic Studies for Improving the Hydrocarbon Prospectivity of the Koroshina Dolomite and Koroshina Anhydrite Formations in the Daw Basin*. Damascus, Syria: Damascus University Publications, 2018.
- [3] A. Alkelany, R. Naser, and K. Malola, "Seismic study of the Sadad gas field in the Daw Basin, Syria," *Damascus Univ. J.*, 2025.

-
- [4] Syrian Petroleum Company, *Internal Well Completion Report, Sadad-2 Well, Sadad Field, Syria*. Damascus, Syria, 2005, unpublished report.
- [5] Syrian Petroleum Company, *Internal Seismic and Exploration Reports*. Exploration Directorate, Regional Geology Department, Damascus, Syria, 2015, unpublished data.
- [6] S. Saleh and A. Alaji, "Petrophysical modelling for reinterpreting hydrocarbon reservoir of Koroshina Anhydrite Formation in the Jazal Field," *Damascus Univ. J.*, 2019.
- [7] W. Zein, M. Aldris, and J. Kafa, "Identification of sedimentary parasequences of Koroshina Dolomite Formation in the Palmyra Series using geophysical well logs analysis," *Aleppo Univ. Res. J.*, 2019.
- [8] M. Al-Kadi and M. Al-Shara, "Sedimentary and palaeogeographic evolution of Koroshina Dolomite Formation in the Palmyrian Belt Zone in Syria," *Damascus Univ. J.*, 2013.
- [9] M. Al-Hamid, *Distribution of Geomechanical Properties in the Omar Oil Field*. Homs, Syria: Homs University Publications, 2021.
- [10] W. Alrhaiyel, *Structural Re-evaluation of the Sadad Field by Creating a 3D Model*. Homs, Syria: Homs University Journal, 2025.
- [11] D. Pelemo-Daniels and R. R. Stewart, "Petrophysical property prediction from seismic inversion attributes using rock physics and machine learning: Volve Field, North Sea," *Appl. Sci.*, vol. 14, Art. no. 1345, 2024. <https://doi.org/10.3390/app14041345>
- [12] E. W. Purnomo, A. H. Abdul Latiff, and M. M. A. A. Elsaadany, "Predicting reservoir petrophysical geobodies from seismic data using enhanced extended elastic impedance inversion," *Appl. Sci.*, vol. 13, Art. no. 4755, 2023. <https://doi.org/10.3390/app13084755>
- [13] J. I. Umoh, G. T. Akpabio, and K. I. Udo, "Estimation of petrophysical parameters using 3-D seismic data from a field in Niger Delta, Nigeria," *Asian J. Geol. Res.*, vol. 6, no. 1, pp. 12–23, 2023.
- [14] M. S. Hossain, M. M. Rahman, M. H. Khatun, and M. R. Haque, "Petrophysical properties assessment using wireline logs data at well #3 of Srikail gas field, Bangladesh," *China Geol.*, vol. 5, no. 3, pp. 393–401, 2022. <https://doi.org/10.31035/cg2022023>
- [15] A. M. Abdulaziz, H. A. Mahdi, and M. H. Sayyoudh, "Prediction of reservoir quality using well logs and seismic attributes analysis with an artificial neural network: A case study from Farrud Reservoir, Al-Ghani Field, Libya," *J. Appl. Geophys.*, vol. 161, pp. 239–254, 2019. <https://doi.org/10.1016/j.jappgeo.2018.09.013>
- [16] B. H. Russell, L. R. Lines, and D. P. Hampson, "Application of the radial basis function neural network to the prediction of log properties from seismic attributes," *Explor. Geophys.*, vol. 34, no. 2, pp. 15–23, 2003. <https://doi.org/10.1071/EG03015>
- [17] Hampson-Russell (CGG), *Guide to Post-Stack Inversion*. Calgary, Canada: CGG, 2015.
- [18] Hampson-Russell (CGG), *Guide to Emerge*. Calgary, Canada: CGG, 2015.
- [19] T. Topór and K. Sowizdzal, "An advanced ensemble modeling approach for predicting carbonate reservoir porosity from seismic attributes," *Geol., Geophys. Environ.*, vol. 49, no. 3, pp. 245–260, 2023. <https://doi.org/10.7494/geol.2023.49.3.245>
- [20] V. Sotelo, O. Almanza, and L. Montes, "Post-stack seismic inversion through probabilistic neural networks and deep forward neural networks," *Earth Sci. Inform.*, vol. 17, pp. 1957–1966, 2024. <https://doi.org/10.1007/s12145-024-01251-4>
- [21] S. Hosseinzadeh, M. R. Saberi, M. Haghighi, A. Salmachi, and S. Salimzadeh, "Seismic inversion approaches for reservoir characterization: A comprehensive review," *J. Appl. Geophys.*, vol. 243, Art. no. 105953, 2025. <https://doi.org/10.1016/j.jappgeo.2025.105953>
-



Improvement Proposals of Al-Kansaa Intersection

Miami M. Hilal^{1*}  , Sarab Mehdy² , Nahla M Salim³  

¹ Highway and Geotechnical Department, Civil Engineering College, University of Technology-Iraq, Baghdad, Iraq.

² The State Corporation for Roads and Bridges, Baghdad, Iraq.

³ Civil Engineering Department, College of Engineering, Al-Naji University, Baghdad, Iraq.

Article Info	ABSTRACT
Received: 10 June 2026 Revised: 29 June 2026 Accepted: 03 July 2026 Available online: 30 September 2026 Keywords: Intersections; Traffic volumes; Level of service; Civil 3D geometric design program; HCS 2010.	Intersections are among the most critical elements of highway networks because they directly influence traffic efficiency, capacity, and safety. This study evaluates improvement alternatives for Al-Kansaa's three-leg intersection in Iraq, which currently experiences severe traffic congestion and operates at Level of Service (LOS) F. Traffic volume surveys and geometric data were collected and analyzed using Highway Capacity Software (HCS2010), while Autodesk Civil 3D was employed to develop and evaluate four geometric improvement alternatives. The existing intersection analysis indicated an average control delay of 398.66 s/veh, corresponding to LOS F. The first improvement proposal, which involved adding a lane to the southbound approach, reduced the average delay to 165.67 s/veh; however, the intersection continued to operate at LOS F, indicating that geometric widening alone was insufficient. Therefore, three grade-separated interchange alternatives were developed and assessed based on operational performance, geometric feasibility, land-acquisition requirements, and constructability. Among the proposed alternatives, the interchange incorporating two bridges and a roundabout was identified as the most suitable solution because it provides smoother traffic operations, minimizes land acquisition, reduces construction constraints, and preserves the operational performance of the major roadway. The findings demonstrate that comprehensive geometric redesign is more effective than minor geometric modifications for improving heavily congested three-leg intersections and may serve as a practical reference for similar intersections in developing countries. The novelty of this study lies in the integrated evaluation of four alternative intersection improvement proposals by combining traffic operational performance, geometric design, constructability, and land-acquisition considerations within a single decision framework for a real-world three-leg intersection.

1. Introduction

Intersections are one of the most critical and complicated elements in highway design. Intersections are planned points of conflict where two or more roadways join or cross, and they

control the efficiency, capacity, and safety for motorized and non-motorized users of the facility. The type and operation of an intersection is important to the adjacent property owners, motorists, bicyclists, pedestrians, transit operators, the trucking industry, and the local community [1].

Al-Khansaa is a 3-leg intersection linking Al-Nahrowan and Diyala. It has a vital role in the local region. It suffers from high congestion and delay, so it needs restoration in order to enhance its performance. Design suggestions for improvements of Al-Khansaa intersection were developed to improve the safety and capacity of the congested intersection because as stated in the AASHTO 2011, the main objective of intersection design is to: "reduce the severity of potential conflicts between motor vehicles, buses, trucks, bicycles, pedestrians, and facilities, while facilitating the convenience, ease, and comfort of people traversing the intersections." [2].

Many researchers have adopted the performance improvement of intersections and analysed the results by using design software programs. For example, Al-Ekaby in 2001 selected the Antar Square intersection, which is part of the Adhamiyah network and located at a congested city center in Baghdad [3]. Al-Ekaby used the Highway Capacity Software HCS program to analyse the intersection data and minimize the intersection delay, and used TRANSYT-7F to test the traffic performance of the intersection and to evaluate and improve the traffic flow patterns of the network. The Iraqi State Corporation for Roads and Bridges suggested enhancing a four-leg intersection on the road of Baghdad-Kut by converting it to a full clover leaf in order to connect the road of Baghdad-Umara with the road Kut-Badra. The intersection was designed with AutoCAD Civil 3D and Land Desktop Companion 2009; the design was completed in 2011. [4]

Another example is Al-Swaira Intersection, which is located on the Baghdad-Kut road. The Iraqi State Corporation for Road and Bridges suggested adding a lane and an overpass road that connects the Al-Swaira road. It has been designed using the Civil 3D program [4]. Improvements suggested by the Iraqi State Corporation for Road and Bridges on the Somer intersection, which is located at Expressway section No.5 (Baghdad-Basra), to connect Daghra with Somer townships in Al-Diwaniyah governorate. The design was done by the AutoCAD Civil 3D Land Desktop Companion 2009 design program; the design was completed in 2012 [4].

Al-Haydari (2011) evaluated the performance of seven selected intersections

located in arterials at the holy city of Karbala; three of them were four-leg signalized intersections, and the remaining four were roundabouts. SYNCHRO software was used in the evaluation and analysis of signalized intersections, and SIDRA intersection software was used in the evaluation and analysis of both signalized intersections and roundabouts. She suggested some improvement proposals which vary from changing the timing plan, geometric improvements, to changing the intersection type completely [5]. Al-Hamzawi (2012) assessed and evaluated traffic performance for the Mohammed Al-Qasim Expressway in Baghdad City by using the Highway Capacity Software HCS 2000 program, which elicited the LOS of basic segments and weaving area sections. Artificial Neural Network ANN and regression models were used to develop the speed and density models of the traffic stream using SPSS 19 [6].

The geometric design of the intersections plays a critical role in managing traffic flow and minimizing congestion [7]. The intricate network of road types and their contributory role in traffic accidents has garnered significant attention in the realm of civil engineering [8].

Ali and Al-Hadad (2025) [9] evaluate traffic conditions on the Kasnazan arterial road (known as Erbil-Koya Road) using field data and VISSIM microsimulation. The analysis focused on peak-hour traffic, geometric road design, and Level of Service (LOS) metrics. Four improvement scenarios were simulated: lane expansion, ramp implementation, driver behavior adjustments, and access point optimization.

Results demonstrated that lane expansion and ramp installations significantly enhanced traffic flow, reducing delays by up to 93% and lowering CO emissions by 63%, while improving LOS to D or C. Driver behavior modifications and access point management also yielded moderate improvements.

Unlike previous studies that evaluated isolated operational improvements, this study integrates operational performance analysis, geometric design, constructability considerations, and land-acquisition constraints into a comprehensive decision framework for selecting the most appropriate interchange configuration for a heavily congested three-leg rural intersection in Iraq. Furthermore, the study presents a real

engineering case that can serve as a practical reference for similar intersections in developing countries. Al-Khansaa intersection, suggestions for improvements will be analysed using Highway Capacity Software and the 3D Civil Geometric Design Program 2014 in order to enhance its performance.

2. Research Aims

The main aims of this research are:

1. Collecting and analyzing the data of the Al-Kansaa intersection.
2. Suggesting many solutions to the intersection and selecting the most appropriate one to enhance the capacity and level of service, and reduce the delay.

3. Description of the Al-Khansaa Intersection Location

Al-Khansaa intersection is located in the area linking Al-Nahrowan and Diyala, as shown in Figure 1.



Figure 1. Location of Al-Khansaa Intersection.

4. Intersection geometric design features

Al-Khansaa intersection consists of three legs. The first leg consists of two lanes with a 10-meter median from Al-Nahrawan City (Road No.3), meets the second leg, which consists of two lanes from Canaan roadway (Road No.1), and the third leg is directed toward Baghdad (Road No.2),

as shown in Figure 2 from the Google Earth application.



Figure 2. An Aerial View Shows the Intersection Area.

5. Data collection

Traffic data were collected manually by a trained survey team from the State Corporation for Roads and Bridges. The survey was conducted simultaneously at three observation stations, as presented in Figure 2, to capture all traffic movements entering and leaving the intersection. Traffic counts were recorded continuously for 12 hours per day (7:00 a.m.–7:00 p.m.) over seven consecutive days. Each hour was divided into four 15-minute intervals to identify peak-hour traffic characteristics and calculate the Peak Hour Factor (PHF).

Vehicles were classified into passenger cars and heavy vehicles (trucks), and the percentage of heavy vehicles was determined for each approach to support the capacity analysis. To ensure data quality, standardized traffic-count forms approved by the State Corporation for Roads and Bridges were used, all survey personnel received prior instructions on the counting procedure, and the completed survey sheets were checked daily for completeness and consistency before being entered into the analysis.

collected traffic-count sheets were reviewed for completeness and consistency before data entry. The percentage of heavy vehicles was calculated for each approach and incorporated into the operational analysis. The processed traffic data were then used as input to Highway Capacity Software (HCS 2010) for estimating capacity, control delay, and Level of Service (LOS).

Table 1. Maximum traffic volumes for the three approaches.

Road No.	Day and Date	Total Volume Baghdad (veh/day)	% of Truck
Road No.1	Wednesday (3/6/2015)	21738	42
Road No.2	Friday 5/6/2015	13100	43
Road No.3	Friday 5/6/2015	12162	41

Table 1 shows that the traffic volume on the road (Canaan-Baghdad) (Road No.1) is higher than the road (Nahrawan-Baghdad) (Road No.3) and the road directed toward Baghdad (Road No.2).

5.1 Road No.1 Canaan–Baghdad Road

The peak hour was from 7 AM to 8 AM on Wednesday 3 / 6/ 2015 in the morning. The peak hour is divided into quarters in order to calculate the peak hour factor (PHF) as shown in Table 2.

Table 2. The data on the peak hour of Road No.1

Time (am)	7:00-7:15	7:15- 7:30	7:30- 7:45	7:45-8:00	Total	PHF
Peak Traffic Volume (veh/h)	700	778	680	642	2800	0.9

5.2 Road No.3 Nahrawan – Baghdad Road.

Friday 5 / 6/ 2015 was the highest traffic volume and the peak hour from 7 am in the morning to 8 am, in the morning as shown in Table 3.

Table 3. Peak hour data of Road No.3.

Time (am)	7:00-7:15	7:15- 7:30	7:30- 7:45	7:45-8:00	Total	PHF
Peak Traffic Volume (veh/h)	370	423	400	294	1487	0.88

5.3 Road No.2 is directed to Baghdad.

Friday 5 / 6/ 2015 was the highest traffic volume, and the peak hour was from 10 am in the morning to 11 am, in the morning as shown in Table 4.

Table 4. Peak hour data of Road No.2.

Time (am)	10:00-10:15	10:15- 10:30	10:30- 10:45	10:45-11:00	Total	PHF
Peak Traffic Volume (veh/h)	400	425	390	370	1585	0.93

6. Data analysis of the intersection

Analysis and assessment of the capacity, level of service, and delay for the unsignalized intersection were done using the Highway Capacity Software HCS-2010 program. Capacity, Level of service, and delay results are presented in Table 5, where the level of service was (F) for the whole intersection.

Table 5. Highway Capacity Software Analysis Results (Capacity, LOS, and Delay).

Properties	Eastbound EB		Westbound WB		Northbound NB		Southbound SB	
	L1	L2	L1	L2	L1	L2	L1	L2
Flow Rate veh/sec.			372	375	393	400	1400	
Service Time sec.			5.3	4.5	5.5	5.3	5.0	
Utilization, x			0.75	0.67	0.86	0.85	2.73	
Dep. Headway, hd			7.28	6.46	7.84	7.63	7.03	
Capacity veh./sec.			494	557	459	472	1400	
Delay sec./veh			29.24	21.74	41.88	40.02	800.40	
LOS			D	C	E	E	F	
Approach								
Delay sec./veh			25.47		40.94		800.40	
LOS			D		E		F	
Intersection Delay: 398.66 sec./veh					Intersection LOS: F			

7. Proposals and Solutions for Improvements

The geometric design of each proposed alternative was developed in accordance with the design recommendations of AASHTO (2004) and the Iraqi Highway Design Manual. All alternatives were evaluated using identical traffic demand, geometric design standards, and operational assumptions to ensure a consistent comparison. The preferred alternative was selected based on several engineering criteria, including operational performance (capacity, delay, and Level of Service), geometric feasibility, construction complexity, land-acquisition requirements, environmental considerations, and overall implementation feasibility. These criteria were used to compare the proposed alternatives

systematically through the decision matrix presented in the revised manuscript.

7.1 Proposal No.1

The level of service for the whole intersection was (F), which is required to enhance the intersection by adding additional lanes for approaches. The SB approach should be improved by adding a lane because the delay of this approach was the greatest (800.4 sec./veh.). The HCS 2010 program was used in the analysis of the new geometric feature suggested for the intersection. The results show that the delay of the SB approach was reduced to 301.72 sec/veh. But the level of service for the intersection is still (F), as shown in Table 6, and it is required to suggest another solution in order to enhance the performance of the intersection.

Table 6. Highway Capacity Software Analysis Results (Capacity, LOS, and Delay).

Property	Eastbound EB		Westbound WB		Northbound NB		Southbound SB	
	L1	L2	L1	L2	L1	L2	L1	L2
Flow Rate veh/sec.			372	375	393	400	800	600
Service Time sec.			5.2	4.4	6.3	6.1	6.0	5.4
Utilization, x			0.75	0.67	0.94	0.93	1.84	1.28
Dep. Headway, hd			7.23	6.42	8.58	8.37	8.27	7.65
Capacity veh./sec.			498	561	420	430	800	600
Delay sec./veh			28.66	21.40	59.83	56.68	405.63	163.16
LOS			D	C	F	F	F	F
Approach								
Delay sec./veh			25.01		58.24		301.72	
LOS			D		F		F	
Intersection Delay: 165.67 sec./veh					Intersection LOS: F			

7.1.1 HDM Procedure to Select Another Solution for the Intersection:

To decide how to select a suggested solution for the intersection, the following procedure is proposed by the Iraqi Highway Design Manual [10]:

The type of intersection will be decided according to the Iraqi Highway Design Manual for the State Corporation for Roads and Bridges. Figure 3 shows a relationship between the PCU 24 hr on the main road and the PCU 24 hr on the minor road.

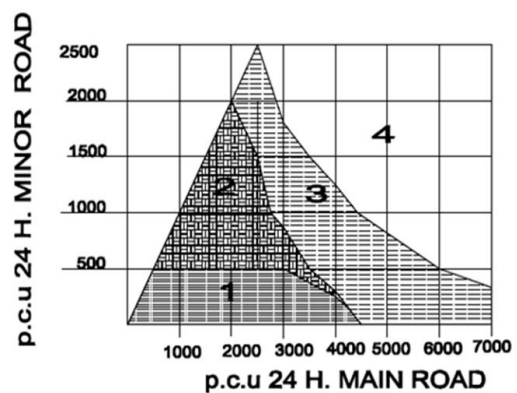


Figure 3. Selection of the type of intersection based on traffic volume [10].

The numbers in Figure 3 refer to the following:

1. Intersection without traffic islands.
2. Divisional and channelizing triangular islands on the minor road.
3. Divisional and channelizing triangular islands on the minor road and a divisional island on the main road.
4. Control the intersection or interchange.

Traffic volume at the Al-Kansaa intersection was projected in the previous figure. The major road was road No.1, and the minor road was road No.3. The analysis of the average daily traffic (ADT) for roads is:

$$ADT = (\text{total weekly traffic} / 7 \text{ days}) \dots (1)$$

Where:

PCU = passenger car unit.

FH = The weighting for each class of vehicle has to be varied to suit the purpose for which they are to be used.

$$ADT \text{ (PCU/day)} = (ADT * (100 - (\% \text{ of truck}))) + (\% \text{ of truck} * FH * ADT) \dots (2)$$

Table 7. Factors of the weight for the class of vehicle [10].

Passenger car/car unit	Light truck car /car unit	Medium (average) Truck /car unit	Heavy goods vehicle/car unit
1	1.25	2	3

Table 8. Volume of traffic on road no.1 (major road) and the proportion of heavy vehicles.

Total volume (vehicle/week)	% of Average Truck/week	Factor of HV (HDM)
130525	42	2

$$ADT = 130525/7 = 18647 \text{ veh/day, say } 18650 \text{ veh/day}$$

$$\text{The number of PCU} = 18650 * ((100 - 42)/100) * 1 + 18650 * ((42/100) * 2) = 26483 \text{ say } 26500 \text{ pcu/day.}$$

Table 9. Volume of traffic on road no.3 (minor road) and the proportion of heavy vehicles.

Total volume (vehicle/week)	% of Average Truck/week	Factor of HV (HDM)
69572	32	2

$$ADT = 69572/7 = 9939 \text{ veh/day, say } 9950 \text{ veh/day}$$

$$\text{The number of PCU} = 9950 * ((100 - 32)/100) * 1 + 9950 * ((32/100) * 2) = 13134 \text{ pcu/day say } 13150 \text{ pcu/day}$$

From the previous calculations, the average volumes of traffic from the major and minor roads during the day require large volumes, so the selected intersection type solution will be an interchange, according to Figure 3.

7.2 Proposal No.2

This suggestion requires connecting the SB approach with the NB approach directly by an underpass, and the WB approach will be connected to the NB approach and the SB approach by a trumpet. The Civil 3D program was used to check the design criteria of the suggested interchange according to the AASHTO 2004 specifications.

Figure 4 shows the interchange geometric design with all details of the proposal. In order to satisfy the specifications criteria, it is required to provide large areas because of the availability of skewed angles and provide long paths in order to achieve the comfort performance for the driver. On the other hand, this suggestion is expensive because the State should buy the adjacent areas as well as the construction cost, so another solution should be suggested.

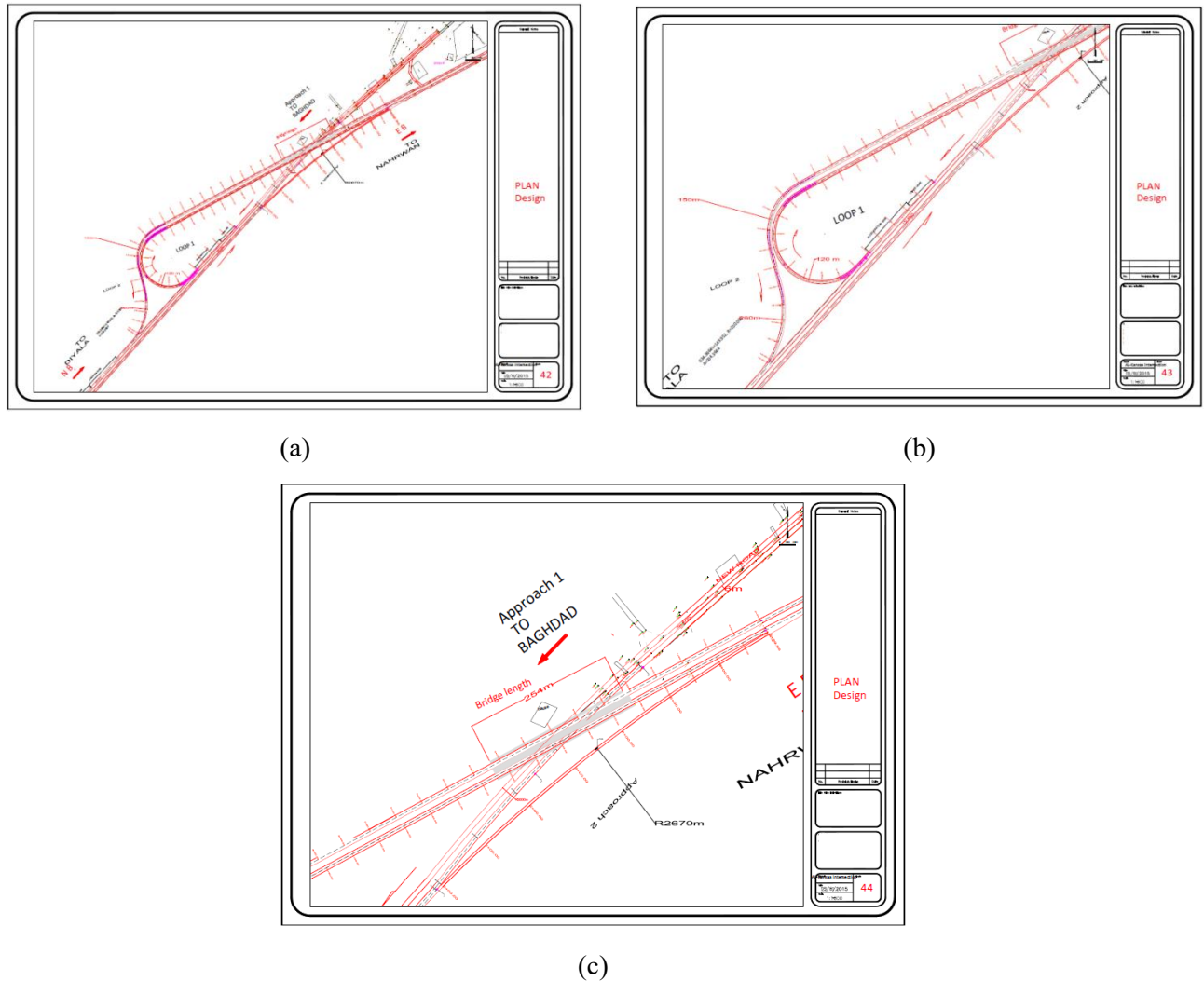


Figure 4. The interchange geometric design of proposal No.2.

7.3 Proposal No.3

To solve the problems of suggestion No.2, this suggestion will present an intersection with 90° angle instead of a skew angle; this will reduce the large areas required in suggestion No.2 and reduce the costs. The solution was a three-leg interchange with a single-structure trumpet. This solution requires shifting the intersection 600 m towards the SB. A team from the State Corporation for Roads and Bridges were done additional survey for the area supervised by the author using the Total Station Device. The

3D Civil program was used to design the suggested interchange.

This proposal design requires short paths to regulate the paths of the interchange approaches and a short bridge length (60 m), and this is a good technical and economic choice, but the interchange passes through the blocks of residential buildings and shops; that's not appropriate environmentally and economically because of the high costs of acquisition. It is required to suggest another solution for the interaction to enhance its performance. Figure 5 shows the geometric design of the interchange with details for each design approach.

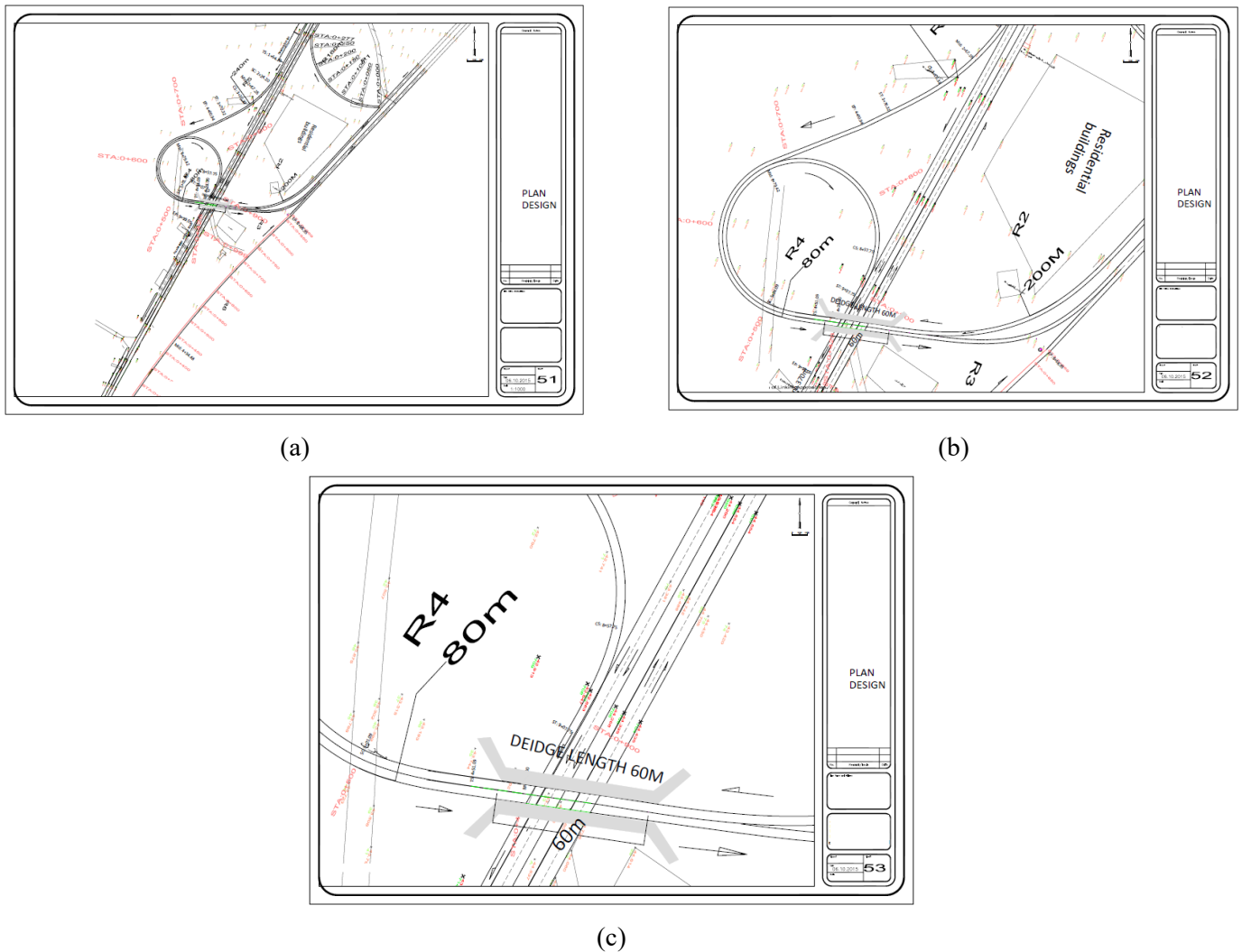


Figure 5. The Geometric Design of Proposal No. 3, shifting the intersection 600 m towards the SB.

7.4 Proposal No. 4

The angle of intersection is proposed to be 15°. The type of the selected design interchange was an overpass with two bridges with a roundabout intersection. The major priority of the movement was for road No.1, which involved two bridges for vehicles going and returning. The roundabout intersection was proposed to connect the WB approach with the service roads of the NB approach and the SB approach.

This suggested solution provides the following:

- It does not require the provision of large areas for the purposes of linking the approaches.
- Reducing the cost of acquisition.

- It provides a great, smooth flow of traffic, and it doesn't affect the performance of the major road.

For the previous reasons, this suggestion will be adopted.

The 3D Civil Design program was used to prepare the geometric design features and drawings for the suggested interchange and verify the proposed geometric design solution.

Approach Cross Section:

Road section design of two-way two-lane with travelled way width in one direction 8.25m, class A4.

- The outer shoulder width is 1.5 m.

- The inner shoulder width is 1.5 m.

The median width is 6m (Note: the median width reduces with the size to reduce the costs of acquisition Conflicts).

Retaining walls have been created on the approaches for a distance of 450 meters north of the bond approach and 300 meters south of the bond approach to provide sufficient space to pass the service roads that connect the roundabout to the bottom of the bridge. Figure 6 shows the typical cross-section of

approaches. Figure 6 presents the typical cross section of the approaches, and Figures 7 to 10 show the geometric design of the interchange with details for each design approach.

Design the inscribed circle diameter by the NCHRP report (Roundabouts: An Information Guide), use the design for a multilane roundabout, 3-lane diameter 120 m and circulatory roadway width 12 m, maximum design speed range (40–50 km/hr). Figure 11 shows the typical cross-section of a roundabout.

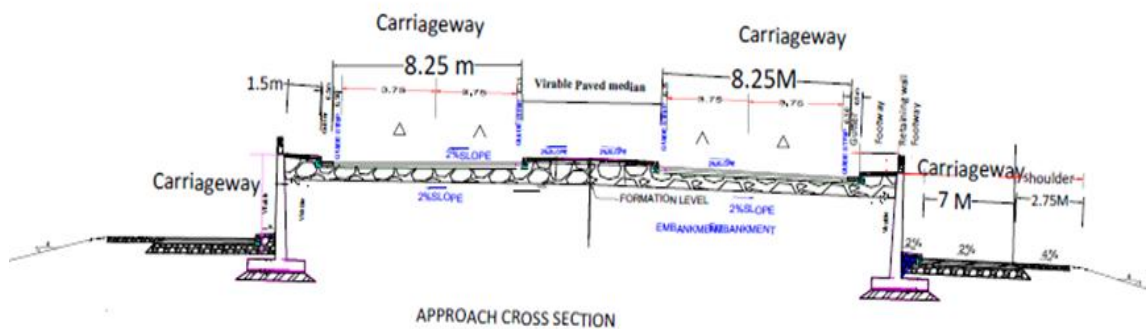


Figure 6. Typical cross-section of approaches.

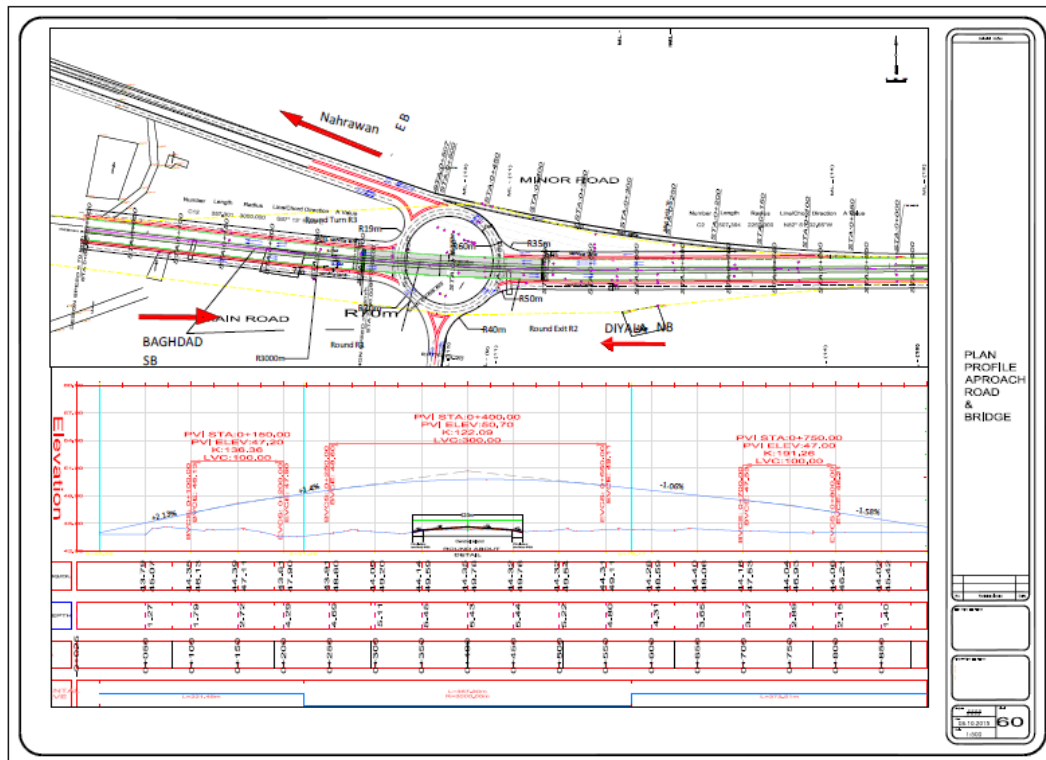


Figure 7. Geometric design of the interchange.

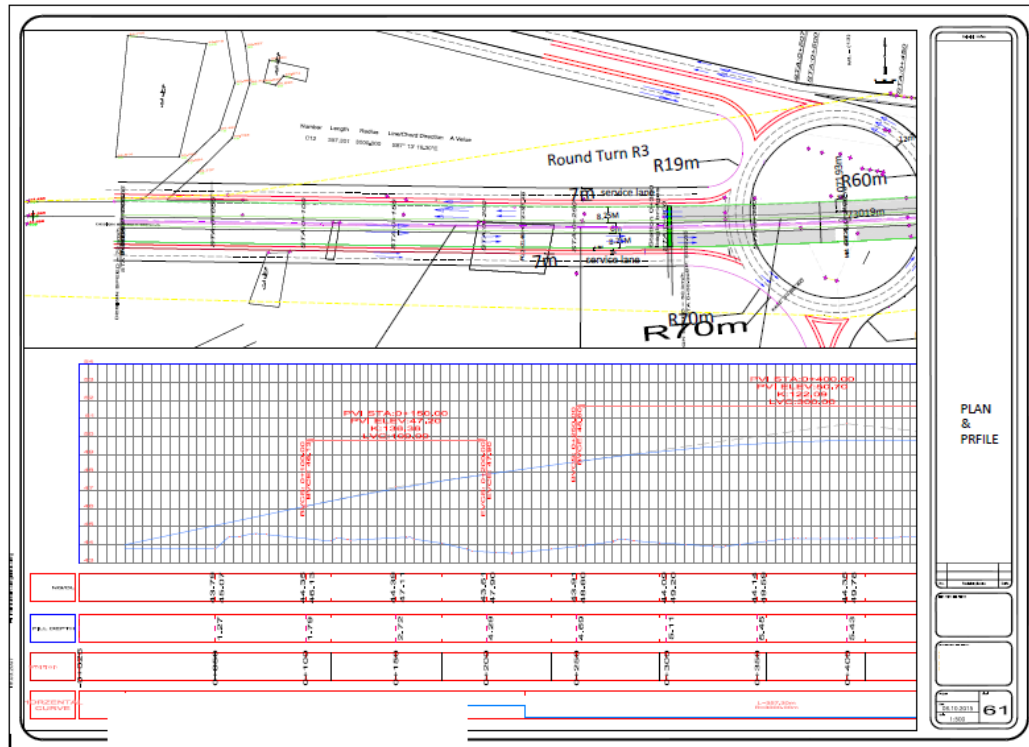


Figure 8. Geometric design of Road No.1.

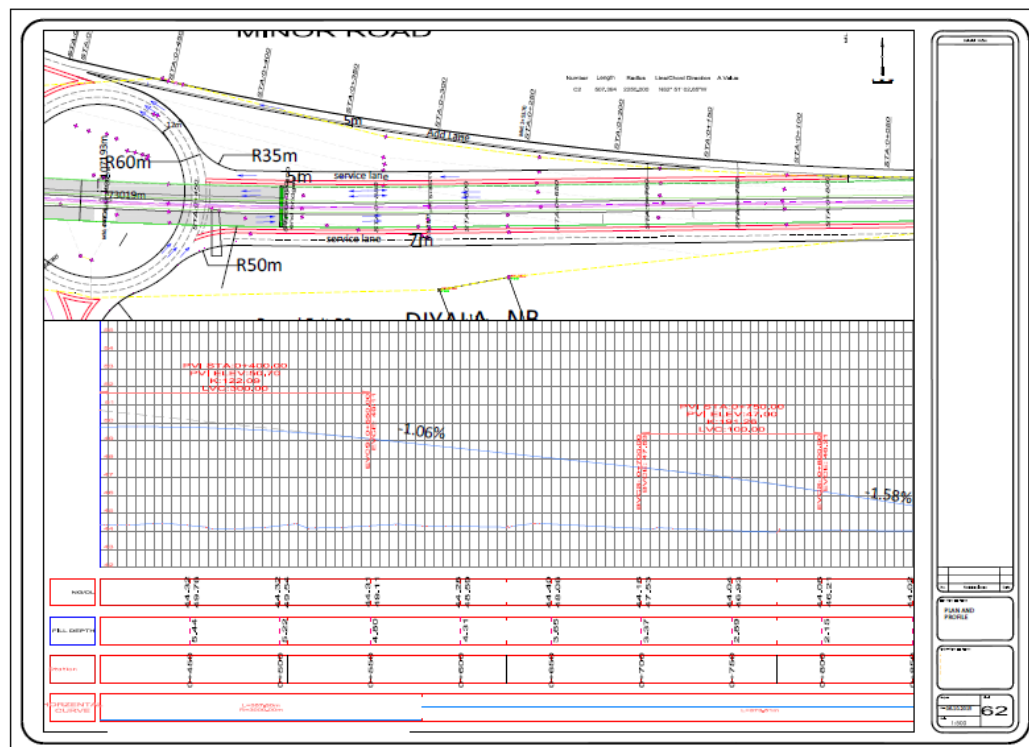


Figure 9. Geometric design of Road No.2.

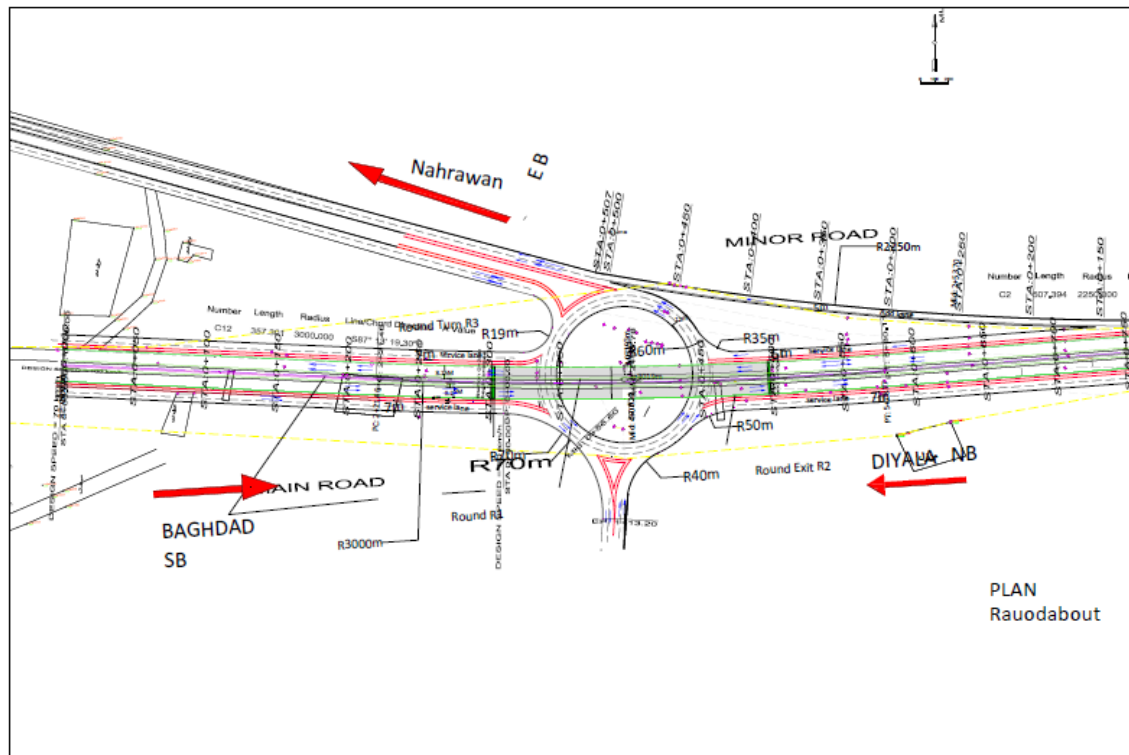


Figure 10. Geometric design of Road No.3.

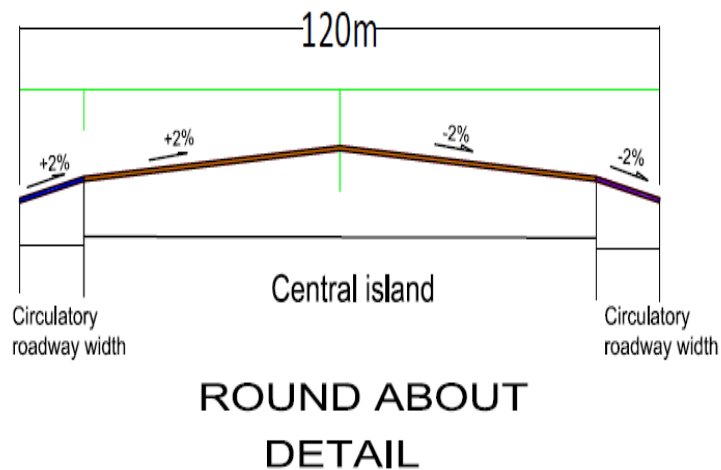


Figure 11. Typical cross-section of a roundabout.

7.5 Comparative Evaluation of the Proposed Alternatives.

To support the selection of the preferred improvement alternative, a comparative decision matrix was developed as presented in Table 10. The four proposed alternatives were evaluated using five engineering criteria that directly influence the feasibility and effectiveness of intersection improvement projects: operational performance, construction cost, land-acquisition

requirements, environmental impact, and implementation feasibility. Each criterion was assigned a qualitative score ranging from 1 (least favorable) to 5 (most favorable) based on the engineering evaluation and comparative assessment presented in this study. The comparison provides a structured basis for selecting the most appropriate alternative.

Table 10. Comparative decision matrix based on the engineering evaluation presented in this study.

Evaluation Criterion	Proposal 1	Proposal 2	Proposal 3	Proposal 4
Operational performance	2	4	4	5
Construction cost	5	2	3	4
Land acquisition	5	1	2	5
Environmental impact	4	2	1	4
Implementation feasibility	5	2	3	5
Total Score	21	11	13	23

Proposal No. 4 is considered the most appropriate alternative as presented in Table 10, which has the highest score among the suggested proposals.

8. Economic Considerations

A qualitative economic assessment was conducted to support the comparison of the proposed alternatives. Proposal No. 1 represents the least expensive option because it only requires widening the southbound approach by adding a lane, with minimal construction work and negligible land acquisition. Proposal No. 2 is expected to have the highest implementation cost due to the construction of a trumpet interchange under skewed geometry, which requires extensive earthworks, longer connecting ramps, and substantial land acquisition. Proposal No. 3 reduces some geometric complexity compared with Proposal No. 2; however, its implementation would require relocation of residential buildings and commercial properties, resulting in considerable land-acquisition and compensation costs. Proposal No. 4 provides a balanced solution by minimizing additional land acquisition while improving traffic operations through grade separation and a roundabout configuration. Although its construction cost is expected to be higher than Proposal No. 1, the reduced right-of-way requirements and improved operational performance make it the most practical and economically feasible alternative among the proposed designs. A detailed cost estimate and benefit-cost analysis are recommended for future

studies after completion of the final engineering design.

9. Safety Considerations of the Preferred Alternative

In addition to the operational improvements, the preferred design is expected to provide significant safety benefits. The proposed interchange separates the major through traffic from intersecting traffic movements by means of grade separation, thereby reducing the number of potential vehicle conflict points. The inclusion of a roundabout for local traffic movements also contributes to improved safety by reducing vehicle speeds at entry and exit points and eliminating high-speed crossing conflicts. Furthermore, smoother traffic flow and lower congestion are expected to reduce sudden braking, aggressive lane-changing, and driver delays, which are common factors associated with traffic crashes. Although a quantitative crash analysis was beyond the scope of this study due to the unavailability of historical accident records, the proposed design is expected to enhance overall traffic safety based on established geometric design and traffic engineering principles.

10. Discussion

The analysis demonstrates that minor geometric modifications alone are insufficient to address severe congestion at Al-Kansaa Intersection. Although Proposal No. 1 reduced the average control delay, the intersection continued to operate at Level of Service (LOS) F, indicating that adding an extra lane cannot adequately accommodate the existing traffic demand. This finding suggests that localized geometric improvements are unlikely to provide a long-term solution for heavily congested intersections with substantial through traffic.

The comparison of the four proposed alternatives showed that Proposal No. 4 provides the most balanced engineering solution. In addition to improving traffic operations through grade separation, the proposed design minimizes land-acquisition requirements, reduces construction constraints compared with the other interchange alternatives, and preserves uninterrupted traffic flow on the major roadway. These characteristics make the proposed design

more practical for implementation under existing site conditions.

From a transportation planning perspective, the findings highlight the importance of considering operational performance together with geometric feasibility, land availability, constructability, and environmental constraints during the selection of intersection improvement projects. The results demonstrate that the preferred solution should not be determined solely by traffic capacity but also by its feasibility, sustainability, and compatibility with the surrounding road network.

The proposed design may also serve as a practical reference for improving similar high-volume three-leg intersections in Iraq and other developing countries where rapid traffic growth, limited right-of-way, and budget constraints present significant challenges for transportation agencies. Furthermore, detailed economic evaluation and quantitative road safety analysis are recommended before implementation of the selected alternative.

11. Conclusions

Many proposals were suggested to enhance the performance of the Al-Kansaa intersection. The following conclusions were presented:

1. Adding a lane in the SB, as presented in the proposal No.1, did not give an improvement as the LOS still (F).
2. The construction of the trumpet intersection with a skew angle, as presented in proposal No.2, was not appropriate because of the availability of a skewed angle, and a long path should be provided in order to achieve the comfort performance for the driver to satisfy the specification criteria.
3. Implementation of the trumpet intersection with a right angle was not appropriate as presented in proposal No.3 because the interchange passes through the blocks of residential buildings and shops; that's not appropriate environmentally and economically.
4. The most appropriate suggestion was proposal No.4 because this proposal provides the following:
 - It does not require the provision of large areas for the purposes of linking the approaches.
 - Reducing the cost of acquisition.
 - It provides a great, smooth flow of traffic, and it doesn't affect the performance of the major road.

Acknowledgements

Authors can express their appreciation to the State Corporation for Roads and Bridges organization for their valuable help in collecting data and support the research with necessary information. The authors also express their appreciation to Al Naji University and University of Technology for their academic support to the research efforts.

Conflict of interest

The authors declare no conflicts of interest concerning this research.

Funding

The authors did not receive support from any organization for the submitted work.

Author Contribution

M.M. Hilal conceived of the presented idea, developed the theory and verified the analytical methods, and supervised the findings of this work. S.Mehdy carried out the experiment, wrote the manuscript and worked out almost all of the technical details. N.M. Salim verified the analytical methods, conceived the original idea and supervised the project. All authors participated in the discussion of the results and contributed to writing the manuscript.

AI Declaration Statement

The authors confirm that the manuscript has been written without the assistance of generative AI or AI-based writing tools.

References

- [1] California Department of Transportation, *Highway Design Manual*, 2014.
- [2] American Association of State Highway and Transportation Officials (AASHTO), *A Policy on Geometric Design of Highways*

- and Streets*, 6th ed. Washington, DC, USA, 2011.
- [3] A. H. Al-Ekaby, "Evaluation and improvement of traffic flow patterns at Antar Square in Baghdad City," M.Sc. thesis, University of Technology, Baghdad, Iraq, Mar. 2001.
- [4] *Archive of Design Plans of the Iraqi State Corporation for Roads and Bridges*.
- [5] I. S. J. Al-Haydari, "Improvement of traffic flow on arterials in Holy Karbala City," M.Sc. thesis, University of Al-Mustansiriyah, Baghdad, Iraq, Jun. 2011.
- [6] I. A. O. Al-Hamzawi, "Descriptive model of existing freeway in Baghdad using artificial neural network (ANN)," M.Sc. thesis, University of Al-Mustansiriyah, Baghdad, Iraq, Jul. 2012.
- [7] D. Zulkarnaen, S. Mayuni, E. Mukti, and N. Nurhayati, "Geometric design of coordinated traffic signal intersections: Case study of four-way intersections at Kapuas II Bridge and Kapur Village," *J. Tek. Sipil*, vol. 24, no. 3, p. 1183, 2024, <https://doi.org/10.26418/jts.v24i3.84088>
- [8] D. K. Hassooni, R. Ghasemlounia, M. M. Hilal, Z. H. Al-Saffar, and G. T. Mohammed, "Analyzing traffic accident trends and correlations in Iraq: An investigative statistical approach," *AIP Conf. Proc.*, vol. 3303, Art. no. 040002, 2025, <https://doi.org/10.1063/5.0264564>
- [9] N. A. Ali and B. M. Al-Hadad, "Enhancing traffic flow efficiency towards sustainability: A case study of Kasnazan arterial road," *Eurasian J. Sci. Eng.*, vol. 11, no. 2, 2025, Art. no. 22, <https://doi.org/10.23918/eajse.v11i2p22>
- [10] State Organization of Roads and Bridges, *Highway Design Manual*. Design and Studies Department, Road and Traffic Division, 2005.



Strength of Clay Treated with Biopolymer Under Cyclic Wetting and Drying

Mohammed Y. Fattah^{1*}  , Mohammed F. Aswad¹  , Nahla M. Salim²  , Teba A. Abd¹ 

¹ College of Civil Engineering, University of Technology-Baghdad, Baghdad, Iraq.

² Civil Engineering Department, College of Engineering, Al-Naji University, Baghdad, Iraq.

Article Info	ABSTRACT
Received: 11 June 2026 Revised: 06 July 2026 Accepted: 06 July 2026 Available online: 30 September 2026 Keywords: Soft soil; Biopolymer; Cyclic, wetting; Drying	The increasing environmental concerns associated with conventional soil stabilization materials, particularly cement, have driven the exploration of sustainable alternatives such as biopolymers. However, the practical application of biopolymer-treated soils remains questionable due to their susceptibility to biodegradation and hydrolysis under fluctuating environmental conditions. This study investigates the durability of clay soil treated with carboxyl methyl cellulose (CMC) biopolymer under cyclic wetting and drying conditions, aiming to evaluate the progressive strength degradation and potential serviceability of such treated soils for temporary or medium-term geotechnical applications. The experimental program employed soft silty clay obtained from southeast Baghdad, Iraq, treated with 5% CMC biopolymer by dry weight of soil. Specimens were prepared at optimum moisture content and subjected to up to five cycles of controlled wetting (submersion in water for 24 hours) and drying (oven drying at 45°C for 24 hours), with unconfined compressive strength (UCS) measurements taken at each drying and wetting phase. The results revealed a progressive reduction in UCS from an initial dry strength of 2050 kN/m² after the first drying cycle to 460 kN/m² after the fifth drying cycle, while wet strengths decreased from 270 kN/m² to 49.5 kN/m² over the same period. Despite this substantial strength loss, partial strength recovery was observed during each re-drying phase, attributed to the re-establishment of polymer-soil bonds upon moisture removal. The study demonstrates that while biopolymer-treated clay exhibits significant vulnerability to cyclic moisture fluctuations due to the hydrophilic nature of CMC and irreversible polymer dissociation, the gradual rather than catastrophic strength degradation suggests potential viability for temporary geotechnical applications where long-term durability is not critical.

1. Introduction

Soil stabilization refers to the addition of a cementing material(s) to the soil to improve one or more of its geotechnical properties. The addition of stabilizing agents to natural soils has a long history either by mechanical mixing to obtain a

homogeneous mixture or by adding the stabilizing material to fill the soil voids [1-3]. Several materials (natural, fabricated and byproduct materials) have been used as stabilizers for adaptation of clayey soils. The application of various inorganic or organic additives such as lime, Portland cement, asphalt binder, fly ash, rice husk ash, silica fume, nanomaterials, etc., or their

combinations often create the modification of soil properties including cementation of soil particles [3-6].

As of late, a few endeavors to fortify soil utilizing natural cycles or discharges (e.g., naturally delivered materials) for development and geotechnical designing applications have been announced [7-10]. For instance, organisms, for example, *Sporosarcina pasteurii* have been infused into soils to participate calcite between the soil particles, which actuates a concrete like impact however with a low carbon impression [10-13]. In the interim, naturally delivered biopolymers have been utilized straightforwardly as blending added substances or binder for soil improvement and fortifying, and have appeared astounding upgrade of between molecule cooperation's, even at low fixations (e.g., a 1% or lower proportion to the mass of soil has yielded unconfined compressive strength higher than 4 MPa) [14 - 16].

A past report including the utilization of xanthan gum biopolymer for soil fortifying showed that xanthan gum blended at 1% substance with Korean remaining soil expanded the compressive strength (4.9 MPa) practically twofold comparative with the compressive strength (2.6 MPa) of 10% concrete treatment on the equivalent soil [17]. Late examinations presented thermo-gelation biopolymers such as gellan gum and agar gum as another treatment folio for clayey and sandy soils [18]. Contrasts in soil types become significant while considering biopolymer-treated soils: both gellan gum and agar gum displayed particularly critical fortifying effectiveness with clayey soils (coming to up to 13 MPa for clayey soils) [14].

Organic methodologies have harmless to the ecosystem benefits because of their low ozone depleting substance discharges [19, 20] and high capacity to forestall soil disintegration [21], while concrete, the most generally utilized restricting material in the field of development and building designing, is known to contribute intensely to carbon dioxide discharges (i.e., concrete creation represents around 7% of complete worldwide outflows) [22].

Considering developing ecological concerns, new development materials and strategies including the utilization of organic cycles and mixtures (for example calcite accelerating miniature organic entities, biopolymers) are being

effectively concentrated to lessen the utilization of concrete in the field of development, particularly for geotechnical designing [23]. The fundamental qualities of concrete that prompted it turning into the most usually utilized material in development and geotechnical designing are its astounding solidness and functionality [23].

Considering growing ecological concerns, new development materials and strategies including the utilization of organic cycles and mixtures (for example calcite-accelerating microorganisms, biopolymers) are being actively studied to reduce the reliance on cement in the field of construction, particularly for geotechnical engineering [23]. The fundamental qualities of concrete that led it to become the most commonly used material are its outstanding durability and workability [23-25].

However, a critical knowledge gap persists: while numerous studies have successfully demonstrated the high initial strength gains of biopolymer-treated soils under optimal, static curing conditions (e.g., [14-18]), the long-term serviceability of these treated soils under real-world environmental fluctuations remains severely underexplored. In natural field conditions, geotechnical structures are inevitably subjected to cyclic moisture changes due to seasonal rainfall, groundwater table variations, and evaporation. Most existing literature focuses on a single wetting or drying event, or purely examines strength at a fixed water content. The progressive physicochemical deterioration caused by repeated wetting-drying cycles—which trigger polymer swelling, hydrolysis, and bond dissociation—has not been systematically quantified for biopolymer-treated clayey soils.

Furthermore, regarding the specific material used in this study, Carboxyl Methyl Cellulose (CMC)—an anionic, water-soluble cellulose derivative—has been widely applied in food and pharmaceutical industries, yet its application in geotechnical soil stabilization has received comparatively less attention than xanthan gum or gellan gum. More importantly, the cyclic durability of CMC-treated soils has never been rigorously examined. The hydrophilic nature of CMC makes it particularly susceptible to moisture fluctuations, yet no prior work has established the rate of strength decay or the potential for partial

recovery under successive drying and submersion events.

Consequently, the novelty of this research lies in the systematic experimental investigation of CMC-treated low-plasticity clay subjected to up to five controlled wetting-drying cycles. Unlike previous works that merely report static strength improvements, this study uniquely quantifies the progressive degradation trajectory of both dry and saturated unconfined compressive strength (UCS), alongside volumetric changes (dry density and water content variations) over multiple cycles. By comparing the stress-strain behavior at each phase, this research aims to determine whether the strength loss follows a sudden brittle failure (typical of cement/lime treatment under cyclic conditions) or a gradual ductile deterioration that might still permit temporary or medium-term construction applications.

Hence, the primary objective of this study is to evaluate the durability of CMC-treated clay under cyclic wetting and drying, identifying the underlying mechanisms of strength loss and partial recovery, while providing practical insights into the feasibility of employing biopolymer-treated soils as an eco-friendly alternative in seasonal climates where long-term permanency is not required.

In this study, the effect of cycles of wetting and drying on durability of biopolymer treated soil will be examined.

2. Experimental Program

2.1. Materials

The soft soil that used in this study has been dispatched from south east of Baghdad city (Iraq) from an old embankment located. The soil was medium to stiff brown silty clay. The delicate soil has been gone through research community tests to find its properties. These tests contain: specific gravity and Atterberg limits (liquid limit (L.L) and plastic limit (P.L)) according to ASTM specification. Standard Proctor test, grain size appropriation (sieve analysis and hydrometer tests) was also conducted. The results show that the soil contains (4%) sand, (30%) silt and (66%) clay. The soil is classified by the Unified Soil Classification System (USCS) as CL; clay soil with low plasticity. Physical and compound properties are shown in Table 1 for the soil used

and the grain size distribution of the soil used appears in Figure 1.

Table 1. Physical and chemical properties of the soil.

Property	Value
Specific gravity (Gs)	2.7
Gravel, (G%)	0
Sand, (S%)	4.3
Silt, (M%)	29.7
Clay, (C%)	66
Liquid limit (L.L) %	39
Plastic limit (P.L) %	24
Plasticity index, (P.I%)	15
Optimum moisture content, (O.M.C %)	18
Maximum dry unit weight (γ_{dry})	19
SO ₃ (%)	0.85
Gypsum content (%)	1.24
pH	9.2
T.S.S.%	1.69

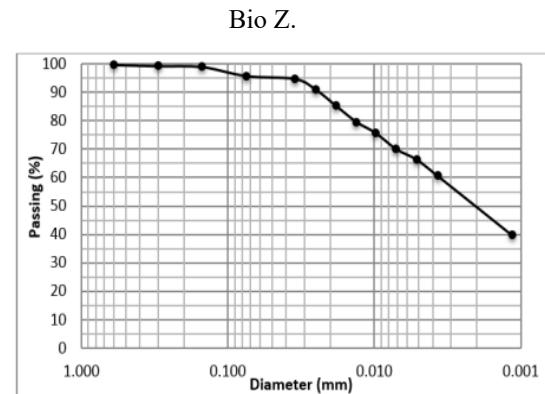


Figure 1. Grain size distribution curve.

Carboxyl methyl cellulose (CMC) is used in the study. It is an anionic, water-solvent cellulose subordinate. Solvency of CMC relies upon the DP just as the level of replacement and the consistency of the replacement dissemination. The water solvency of CMC would increase with diminished DP (Degree of Polymerization) and expanded carboxymethyl replacement and replacement consistency. Specifically, DP refers to the number of repeating monomeric units (glucose units) in the cellulose polymer chain that makes up the Carboxyl Methyl Cellulose (CMC). The consistency of the arrangement increments with expanding DP and expanding fixation [23]. Figure 2 shows sample of CMC used in this study.



Figure 2. Carboxymethyl cellulose bio-polymer.

CMC is the significant cellulose ether. By enacting the noncrystalline locales of cellulose, particular districts of alkylating reagents can assault the cellulose. This is named the idea of responsive construction parts and is utilized broadly for the creation of CMC. Another course for completing a similar response is by derivatization of cellulose in receptive microstructures, shaped by prompted stage partition. This interaction includes the utilization of NaOH in anhydrous state in blend with solvents like DMA/LiCl. These CMC items have a circulation of substituents that veer off fundamentally from factual forecast of the item hypothetically [23].

CMC is a subsidiary of cellulose, containing carboxymethyl bunches that are created through the response of cellulose with chloroacetate in salt to deliver replacements in the C2, C3, or C6 places of glucose units. Accordingly, CMC is water solvent and more manageable to the hydrolytic action of cellulases. CMC is in this way a valuable added substance to both fluid and strong vehicles for the identification of cellulase action, and its hydrolysis can be accordingly dictated by the utilization of the color Congo red, which ties to unblemished β -d-glucans. Zones of clearing around states becoming on strong medium containing CMC, hence finished with Congo red, gives a helpful measure to identifying hydrolysis of CMC and subsequently, β -d-glucanase action [22].

To ensure reliable and repeatable results, the characterization of CMC for such research typically follows established standards, most notably ASTM D1439, which is the standard test method for Sodium Carboxymethyl Cellulose. This standard covers the determination of properties like purity, DS, and viscosity.

In conclusion, while the specific batch details are missing, the CMC was very likely a laboratory-synthesized, technical-grade product with a purity of around 80-90%, a DS of at least 0.80, and a

specific viscosity chosen for the experiment. To be certain, the original authors should be consulted for the exact Certificate of Analysis (COA) of the material used.

2.2 Samples Preparation

Synthesis of CMC was carried out in two steps, alkalization and etherification of pure cellulose under heterogeneous conditions. In alkalization step, 1 gram of cellulose powder of purun tikus was weighed and added to 20 ml of isopropanol with continuous stirring. Then, 4 mL of NaOH solution (5-25%; w/v) was added to the mixture while further stirring for an hour at room temperature. The carboxymethylation was started when monochloroacetic acid (0.6; 0.8; 1.0; 1.2; and 1.4 g) was added with continuous stirring for another at 55 °C for 3 hours. The slurry was neutralized with 90 % of acetic acid to pH 7 and then filtered, and washed with ethanol 70%, dried at 60 °C in the oven and kept in a dry place for further characterization.

A certain amount of soil was taken after it was dried and milled to obtain a fine powder. The biopolymer was added to the soil in a dry manner at room temperature, at a rate of 5% of the total soil weight. The polymer was mixed with the soil and in dry manner until the mixture was homogeneous with the clay soil particles, after which water was added gradually with continuous mixing [26]. The added water is the optimum moisture content that was previously calculated by compaction test.

After homogeneity of the mixture of soil, polymer and water, samples were taken with dimensions of 38 mm in diameter and 76 mm in height more than 15-cylinder samples were prepared at once, all samples were leave at room temperature for about 2 hours. Past examinations with biopolymer as a thermo biopolymer for soil improvement showed that the strength changeability of biopolymer treated soils was generally subject to the dampness substance of the examples [27]. Along these lines, in this examination the temperature also, stickiness of the examples was left at uniform conditions notwithstanding the characteristic changes in climate to disengage the impacts of the wetting and drying cycles on the soil samples.

At the outset, the unconfined compressive strength (UCS) of the initial specimens was

measured immediately after the 2-hour resting period. Three replicate specimens were tested, and the average UCS value was recorded along with the standard deviation to establish the baseline reference strength.

2.3 Experimental Procedure

At the first the unconfined compressive strength UCS of the first sample was taken immediately (after 2 hours of preparation). Then all other samples were placed in a metallic container and entered into an oven at 45°C for 24 hours.

After drying, a cylindrical specimen was randomly selected from the group to obtain its UCS and find the (q_u) from the stress strain curve. The other samples then submerged in water by a hollow plastic cylinder perforated by all sides (to keep the samples from fragmenting while submerging in the water) for another 24 hours, then a specimen was selected randomly to obtain the (q_u). Then both of the dry and wet (q_u) of the first cycle were evaluated. Order of the experimental testing conditions is shown in Table 2.

Table 2. Experimental testing conditions.

Cycle No.	0	1	2	3	4	5
Initial	1					
Drying		2	4	6	8	10
Wetting		3	5	7	9	11

All other samples were dried for another 24 hours at 45°C in the oven, and the (q_u) for the

second cycle was then evaluated by following the same steps mentioned previously until the fifth cycle.

3. Results and Discussion

The stress - strain relationship of the first dry condition cycle of the biopolymer treated soil is shown in Figure 3 and the relationship between No. of cycles and the unconfined compressive strength is shown in Figure 4.

From Figure 4, it can be seen that the biopolymer processing clay increases the unconfined compressive strength and failure strain of biopolymer treated clay, regardless of the humidity condition indicating that the biopolymer is preserved on the adhesion between the particles and the tensile strength effectively on the clay's granular structure against the deformation caused by high stress. Thermal effect of the polymer results in a matrix which has the major role of increasing the durability of the treated soil. This increase in strength should be stable regardless of time if there is no difference in moisture content of the soil [24]. The dry strength of biopolymer – treated soil decreases with increasing wetting and drying cycle as indicated in Figure 4. This means that there is an increase of polymer disorder and high ductility of soil.

The stress - strain relationship of the first wet condition of the biopolymer treated soil is shown in Figure 5 and the relationship between No. of cycles and the unconfined compressive strength is shown in Figure 6.

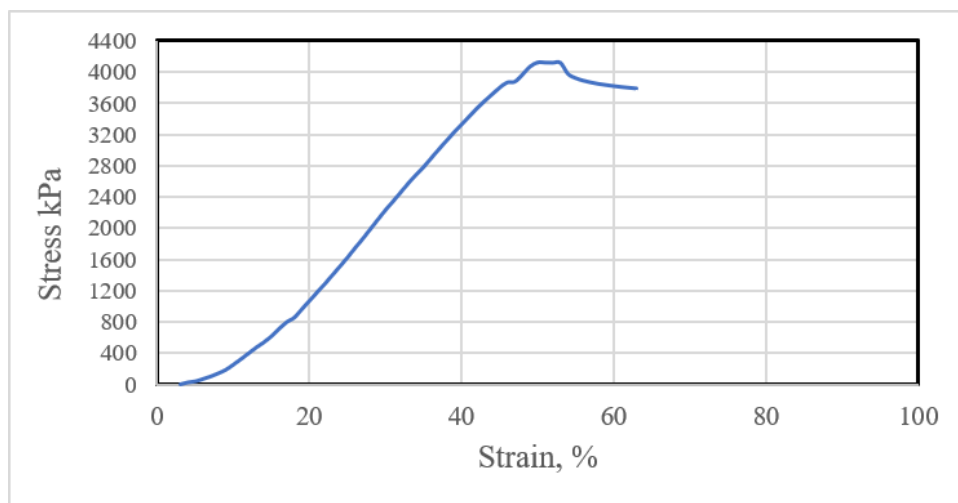


Figure 3. Stress - strain relationship for the sample tested after the first drying cycle.

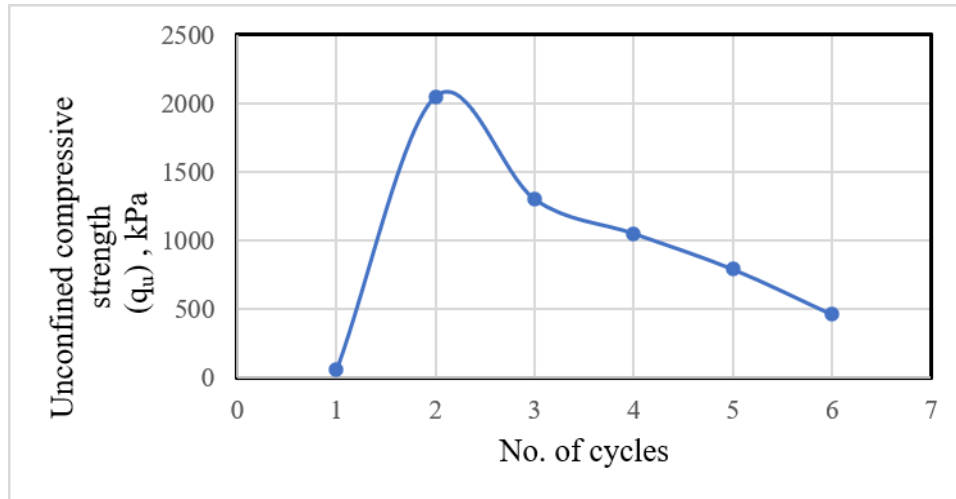


Figure 4. Relationship between number of cycles and unconfined compressive strength at dry conditions. Data points represent mean values from three replicate specimens; error bars indicate $\pm$ one standard deviation.

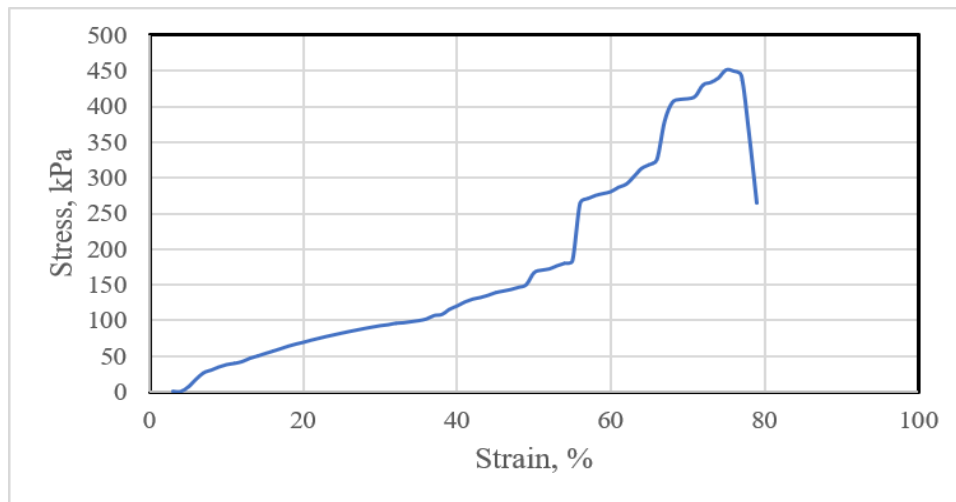


Figure 5. Stress - strain relationship of the first dry cycle.

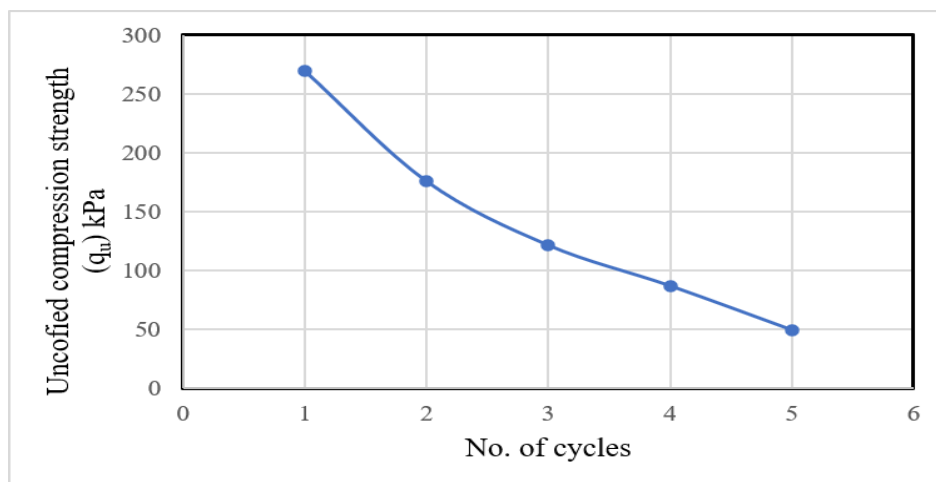


Figure 6. Relationship between number of cycles and unconfined compressive strength at wet conditions. Data points represent mean values from three replicate specimens; error bars indicate $\pm$ one standard deviation.

Figure 6 shows a reduction of the strength of the soil treated with biopolymer after submerging

in water, due to the breakage of the bonds between the polymer and soil particles and soil failure due

to the entry of water molecules between soil and biopolymer, the strength of the soil stiffness decreases and the sample fails under the pressure of influence. Both of the unconfined compressive strength and the volumetric strength were evaluated after each cycle at 1% strain rate or 0.5% mm/min by triaxial device and the results were recorded as shown in Table 3.

Table 3. Unconfined compressive strength of cycled samples.

Cycle	q_u (kN/m ²)	
	Drying	Wetting
Initial	57.5	-
1	2050	270
2	1300	176
3	1050	121.5
4	790	87
5	460	49.5

Dried and wet qualities show a wavering around the underlying strength, demonstrating that despite the fact that the wetting measures include a critical decrease in strength, the ensuing drying in part recuperates the strength of the biopolymer-treated soil, not impeccably, however near the past dried condition.

The debasement of both wet and dry strength of biopolymer-treated soils can be credited to the hydrophilic property of the biopolymer [28, 15]. When dry polymers exposed the clay particles presented to water, they pull out water from the external surface, and the polymer particles separate from the fundamental construction. Separate polymer atoms have essentially no associations with the excess soil design, and this

division is joined by a reduction in both the wet (soaked) strength and the safe (most extreme) strain.

In the interim, when the wet polymer-soil combinations are re-dried, the separated polymer particles connect to the leftover polymer-soil matrix because of the deficiency of moisture, however the first structure isn't recuperated. Because of this severe and re-drying cycle, the general strength reduces. With this cyclic crumbling, the dried polymer will in general lose its density, bringing about a more ductile structure and a bigger most extreme strain. This clarifies why polymer-treated soil shows a continuous strength decrease under cyclic wetting and drying, rather than showing an abrupt breakdown at the early strides of cyclic wetting and drying, as is ordinarily seen in concrete or lime-treated soils [28, 29]. The water content and dry density variation of biopolymer-treated soil under cyclic wetting and drying is shown in Figures 7 and 8.

The results generally show a volumetric change during moisturizing and drying cycles as volumetric shrinkage occurs during the drying of the soil. On the other hand, volumetric expansion of the soil with wetting occurs due to the property of high-water absorption by the biopolymer.

At the same time, with increasing wetting and drying cycles, more polymer particles separate with soil from the base structure of the specimens, reducing the total samples weight and amount of swelling of the wet specimens. Therefore, the moisture density decreases with increasing the number of wetting and drying cycles.

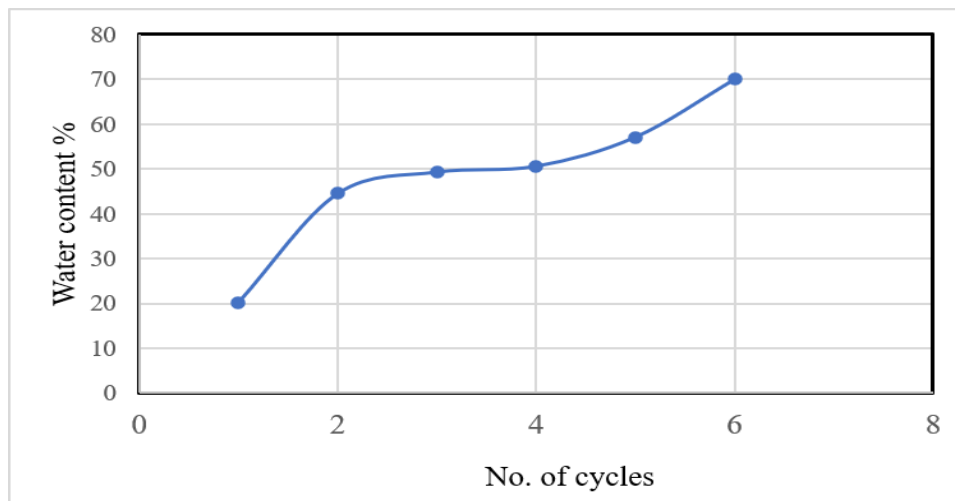


Figure 7. Water content variation with No. of cycles.

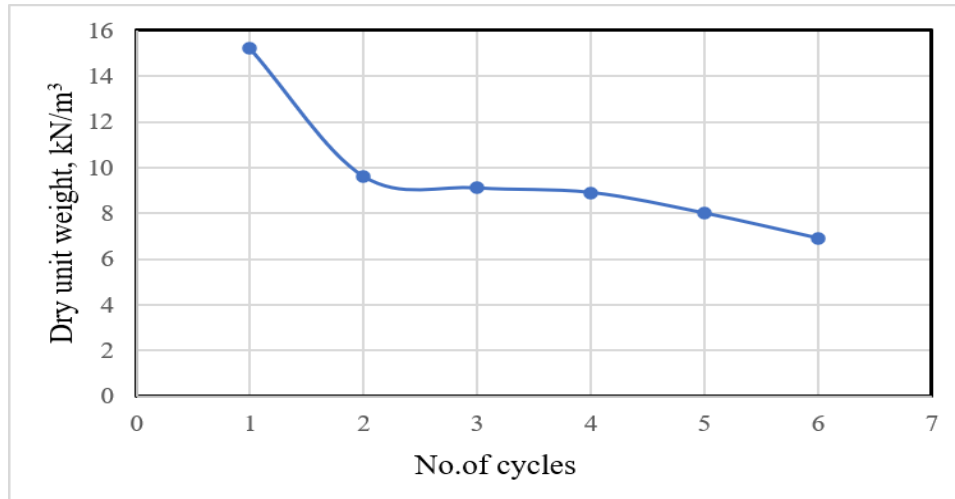


Figure 7. Dry unit weight variation with No. of cycles.

However, dried samples show higher recovery and resistance for drying and moistening cycles, this due to the close proximity of the polymer and soil particles together and the increased of dry density cause to regain a portion of the unconfined compressive strength.

The reproducibility of the UCS measurements was assessed through triplicate testing. The coefficient of variation (CV) across all conditions ranged from 4.2% to 8.5%, indicating acceptable experimental repeatability. Notably, the wetting phases consistently exhibited higher variability ($CV \approx 6.5\text{--}8.5\%$) compared to the drying phases ($CV \approx 4.2\text{--}5.7\%$). This increased scatter under saturated conditions is likely attributable to the hydrophilic swelling behavior of the CMC biopolymer, which can induce localized microstructural heterogeneities and uneven water distribution within the specimens. Conversely, the lower variability observed in dried specimens reflects more uniform polymer–soil bonding and densification during the drying process. The error bars presented in Figures 4 and 6 confirm that the observed trends in strength degradation with increasing cycles are statistically significant, as the standard deviations do not overlap between consecutive cycles.

Then again, the dry densities of wet samples increase with cyclic wetting and drying. For the essential drying, biopolymer monomers collect around soil particles, particularly close to the between molecule contact focuses between the clay particles, due to matrix suction. Notwithstanding, when dried biopolymer is

presented to water once more, hydrophilic expanding of the polymer repulses clay particles, which incites in general volumetric extension of the clay. In the interim, with additional wetting and drying cycles, more biopolymer monomers disassociate from the principal structure, which lessens the aggregate sum of expanding for wet samples. Therefore, the general dry density of immersed biopolymer-treated dirt increments with a higher number of cycles.

The results of this study demonstrate that cyclic wetting and drying significantly influence the mechanical behavior of biopolymer-treated clay. The progressive decline in unconfined compressive strength (UCS) with increasing cycles, as shown in Table 3 and Figures 4 and 6, reveal the vulnerability of biopolymer-treated soils to moisture fluctuations. This degradation is attributed to the hydrophilic nature of carboxyl methyl cellulose (CMC), which swells upon wetting and contracts during drying, leading to repeated microstructural rearrangement and bond weakening.

The reduction in strength is more pronounced in wet conditions, where UCS values dropped sharply compared to dry states. This can be explained by the disruption of polymer–soil bonds due to water infiltration, which reduces interparticle friction and cohesion. Interestingly, the dry strength after each wetting phase did not fully recover to its previous level, indicating irreversible damage to the polymer matrix. This suggests that while biopolymers can enhance soil strength temporarily, their long-term durability

under cyclic environmental conditions remains a challenge.

The observed volumetric changes—shrinkage during drying and expansion during wetting—further support the notion that biopolymer-treated soils are sensitive to moisture content. These volume changes can lead to the development of desiccation cracks and loss of structural integrity, which may compromise the serviceability of biopolymer-stabilized ground in field applications.

Despite the strength reduction, the treated soil retained a measurable level of strength even after five cycles, indicating that biopolymer treatment could still be viable for temporary or medium-term geotechnical applications, such as erosion control, temporary access roads, or short-life infrastructure in arid and semi-arid regions.

When compared to traditional stabilizers like cement or lime, biopolymer-treated soil shows a more gradual strength loss rather than sudden brittle failure. This ductile behavior may be advantageous in certain applications where flexibility and gradual failure are preferable to catastrophic collapse.

Future studies should explore the use of hydrophobic or cross-linked biopolymers, polymer blends, or surface modification techniques to improve water resistance. Additionally, field trials under real climatic conditions are necessary to validate laboratory findings and assess long-term performance.

In summary, while biopolymer treatment offers an eco-friendly alternative to conventional stabilizers, its application must consider environmental exposure, especially in regions subject to frequent wetting–drying cycles.

It is important to note that the reported strength values represent the mean of three replicate specimens tested under identical conditions. The coefficient of variation (CV) for the UCS measurements ranged from 4.2% to 8.5% across all testing conditions, indicating acceptable experimental repeatability and confirming that the specimen preparation and mixing procedures produced a relatively homogeneous soil-polymer mixture. The highest variability (CV $\approx$ 8.5%) was observed during the wetting phases, likely attributable to the uneven water absorption and swelling behavior of the hydrophilic CMC

polymer, which introduces micro-scale heterogeneity in the saturated specimens. In contrast, the dry-phase measurements exhibited consistently lower variability (CV $\approx$ 4.2% to 5.7%), reflecting the more uniform polymer-soil bonding achieved during the drying process.

3.1 Comparison with Gellan Gum-Treated

Gellan gum, a thermo-gelation biopolymer, has shown exceptional durability under cyclic wetting–drying. Studies on gellan gum-treated Korean sand reported that dry strength remained approximately 80% even after severe wetting–drying cycles [10]. The strength reduction over 10 cycles was approximately 30%, with a hysteretic strength path observed along the wetting–drying cycles [10]. Similarly, gellan gum-treated shales and glacial tills maintained 82% and 60% of their initial shear strength, respectively, after 16 weathering cycles.

The superior performance of gellan gum compared to CMC can be explained by its thermo-gelation: gellan gum forms a three-dimensional gel network upon cooling, creating a more robust and resilient polymer matrix within the soil [18]. In contrast, CMC does not exhibit thermo-gelation behavior; its strengthening mechanism relies primarily on hydrogen bonding and electrostatic interactions, which are more susceptible to disruption by water molecules.

Nevertheless, both gellan gum and CMC share a common degradation mechanism: dissociation of polymer monomers during wetting and imperfect recomposition during re-drying [10]. This similarity validates the mechanistic interpretation presented in the current study, while the quantitative differences highlight the superior durability of gellan gum for long-term applications.

3.2 Comparison with Other Biopolymers

Inulin biopolymer has recently emerged as a promising soil stabilizer, with studies reporting a 40-fold increase in UCS (up to 8 MPa) for samples treated with 2% inulin, and only 0.22% weight loss after ten wetting–drying cycles. The deterioration in stiffness and strength was less noticeable after the third cycle, indicating excellent durability [11]. The remarkable performance of inulin is attributed to molecular (hydrogen) bonding facilitated by hydroxyl

groups, forming a durable biopolymer hydrogel–soil matrix [11]. This performance far exceeds that of CMC, suggesting that inulin may be a superior alternative for applications requiring long-term durability.

Sticky rice (SR) biopolymer, used in construction for millennia, demonstrated higher resilience under W-D cycles than xanthan gum, remaining intact after eight cycles with only 1.1% mass loss by the sixth cycle [14†L18-L20]. The hydrophobic nature of SR's coating was identified as the underlying mechanism for its exceptional water resistance [14]. This finding underscores the importance of biopolymer hydrophobicity in determining cyclic durability—a property that CMC, being highly hydrophilic, critically lacks.

Guar gum and xanthan gum have been shown to maintain up to 45% of their initial strength during seven wetting–drying cycles, with some damaged soil–biopolymer bonds being restored with proper treatment. Notably, repeating the wetting–drying process can reactivate the bonding properties of biopolymers, amending broken bonds in soil—a regenerative property that the present study also observed, albeit to a lesser extent, with CMC [13].

4. Conclusions

In this article, the durability of biopolymer-treated soils was tested under periodic wetting and drying through arrangement from laboratory tests. These cycles resulted in a gradual deterioration in the strength and stiffness of the soil against the applied compressive forces due to the separation of the biopolymer particles under the wetting and incompletely reconstituted during re-drying. The following conclusions could be drawn:

1. When polymer and soil are blended at first it is uncovered for drying, the dry density of polymer treated soil increments as the moisture content declines, which causes significant volumetric shrinkage of pore-filling polymeric materials. It diminishes the distances between the clay particles because of the dry shrinkage of the polymer Hydrogels apply an elastic power on the clay particles, and in this way diminishing the general sample size, while expanding both dry density and unconfined compressive strength of treated soil.

2. Decreasing the dry density of dried samples with increasing the cycle number because of decreasing the tensile strength provided by the polymer hydrogels with increase of wetting and drying cycles. As a result, polymer monomer interactions are reduced due to the overlapping of water molecules.
3. The utilization of biopolymer can give a harmless to the ecosystem approach in development and geotechnical designing. polymer, not at all like concrete, doesn't need development destruction, squander treatment, or removal, yet rather can be normally disintegrated (i.e., biodegradation) after the normal help time of the biopolymer-treated soil structures in the field.

5. Limitations

In conclusion, while the cyclic wetting–drying behavior of CMC-treated clay poses significant challenges for permanent geotechnical infrastructure, it does not preclude its use in temporary and medium-term applications within arid and semi-arid climates. By adopting conservative design parameters, implementing robust drainage and surface protection, and embracing proactive maintenance, practitioners can successfully deploy CMC as a sustainable, cost-effective alternative to cement for low-risk projects. The key lies in managing expectations: CMC-treated soils are not a "drop-in" replacement for cement in all scenarios, but rather a specialized solution for specific environmental and service-life conditions where their eco-friendly attributes and gradual failure mode offer distinct advantages.

The limitations of this study can be summarized as follows:

1. Single Biopolymer Type and Dosage.
2. Single Soil Type
3. Limited Number of Wetting–Drying Cycles.
4. Laboratory-Synthesized Biopolymer.
5. Single Testing Method.
6. Limited Stress–Strain Analysis.
7. Scanning Electron Microscopy (SEM) to visualize polymer film morphology, particle bonding, and cracking patterns. X-ray Diffraction (XRD) or Fourier-

Transform Infrared Spectroscopy (FTIR) to detect chemical changes or polymer–soil interactions.

Acknowledgements

The authors express their appreciation to the University of Technology-Iraq for academic support to the research efforts.

Conflict of interest

The authors declare no conflicts of interest concerning this research.

Funding

No funding was received for conducting this study.

Author Contribution

M.Y. Fattah proposed the research problem. M.F. Aswad developed the theoretical framework. N.M. Salim, T.A. Abd verified the analytical methods. All authors participated in the discussion of the results and contributed to writing the manuscript.

AI Declaration Statement

The authors confirm that the manuscript has been written without the assistance of generative AI or AI-based writing tools.

References

- [1] W. H. Perloff, *Soil Mechanics: Principles and Applications*. Minnesota, USA: John Wiley & Sons, 1976. ISBN: 0894646427.
- [2] A. Ates, “The effect of polymer-cement stabilization on the unconfined compressive strength of liquefiable soils,” *Int. J. Polymer Sci.*, vol. 2013, Art. no. 356214, 2013. <https://doi.org/10.1155/2013/356214>
- [3] Y. M. Kadhim, R. A. J. Al-Adhamii, and M. Y. Fattah, “Geotechnical properties of clayey soil improved by sewage sludge ash,” *J. Air Waste Manage. Assoc.*, vol. 22, no. 1, pp. 34–47, 2022. <https://doi.org/10.1080/10962247.2020.1862939>
- [4] K. W. Abd Al-Kaream, M. Y. Fattah, and M. K. Hameedi, “Compressibility and strength development of soft soil by polypropylene fiber,” *Int. J. Geomate*, vol. 22, no. 93, pp. 91–97, 2022. <https://doi.org/10.21660/2022.93.3206>
- [5] A. A. S. Al-Dossary, A. M. Awed, A. R. Gabr, M. Y. Fattah, and S. M. El-Badawy, “Performance enhancement of road base material using calcium carbide residue and sulfonic acid dilution as a geopolymer stabilizer,” *Constr. Build. Mater.*, vol. 364, Art. no. 129959, 2023. <https://doi.org/10.1016/j.conbuildmat.2022.129959>
- [6] M. K. Hameedi, M. Y. Fattah, and R. R. Al-Omari, “Creep characteristics and pore water pressure changes during loading of water storage tank on soft organic soil,” *Int. J. Geotech. Eng.*, vol. 14, no. 5, pp. 527–537, 2020. <https://doi.org/10.1080/19386362.2019.1682350>
- [7] I. Chang, J. Im, and G.-C. Cho, “Introduction of microbial biopolymers in soil treatment for future environmentally-friendly and sustainable geotechnical engineering,” *Sustainability*, vol. 8, no. 3, Art. no. 251, 2016. <https://doi.org/10.3390/su8030251>
- [8] M. K. Ayeldeen, A. M. Negm, and M. A. El Sawwaf, “Evaluating the physical characteristics of biopolymer/soil mixtures,” *Arab. J. Geosci.*, vol. 9, Art. no. 371, pp. 1–13, 2016. <https://doi.org/10.1007/s12517-016-2366-1>
- [9] R. A. Nugent, G. P. Zhang, and R. P. Gambrell, “Effect of exopolymers on the liquid limit of clays and its engineering implications,” *Transp. Res. Rec.*, vol. 2101, pp. 34–43, 2009. <https://doi.org/10.3141/2101-05>
- [10] J. T. DeJong, M. B. Fritzges, and K. Nusslein, “Microbially induced cementation to control sand response to undrained shear,” *J. Geotech. Geoenviron. Eng.*, vol. 132, no. 11, pp. 1381–1392, 2006. [https://doi.org/10.1061/\(ASCE\)1090-0241\(2006\)132:11\(1381\)](https://doi.org/10.1061/(ASCE)1090-0241(2006)132:11(1381))
- [11] J. T. DeJong, B. M. Mortensen, B. C. Martinez, and D. C. Nelson, “Bio-mediated soil improvement,” *Ecol. Eng.*, vol. 36, no. 2, pp. 197–210, 2010. <https://doi.org/10.1016/j.ecoleng.2008.12.029>

- [12] L. van Paassen, R. Ghose, T. van der Linden, W. van der Star, and M. van Loosdrecht, "Quantifying biomediated ground improvement by ureolysis: Large-scale biogrout experiment," *J. Geotech. Geoenviron. Eng.*, vol. 136, no. 12, pp. 1721–1728, 2010. [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000382](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000382)
- [13] V. S. Whiffin, L. A. van Paassen, and M. P. Harkes, "Microbial carbonate precipitation as a soil improvement technique," *Geomicrobiol. J.*, vol. 24, no. 5, pp. 417–423, 2007. <https://doi.org/10.1080/01490450701436505>
- [14] I. Chang and G.-C. Cho, "Strengthening of Korean residual soil with β -1,3/1,6-glucan biopolymer," *Constr. Build. Mater.*, vol. 30, pp. 30–35, 2012. <https://doi.org/10.1016/j.conbuildmat.2011.11.030>
- [15] I. Chang, A. K. Prasadhi, J. Im, and G.-C. Cho, "Soil strengthening using thermogelation biopolymers," *Constr. Build. Mater.*, vol. 77, pp. 430–438, 2015. <https://doi.org/10.1016/j.conbuildmat.2014.12.116>
- [16] D. B. Ringelberg, D. M. Cole, K. L. Foley, C. M. Ruidaz-Santiago, and C. M. Reynolds, "Compressive strength of soils amended with a bacterial succinoglycan: Effects of soluble salts and organic matter," *Can. Geotech. J.*, vol. 51, no. 7, pp. 747–757, 2014. <https://doi.org/10.1139/cgj-2012-0369>
- [17] I. Chang, J. Im, A. K. Prasadhi, and G.-C. Cho, "Effects of xanthan gum biopolymer on soil strengthening," *Constr. Build. Mater.*, vol. 74, pp. 65–72, 2015. <https://doi.org/10.1016/j.conbuildmat.2014.11.026>
- [18] I. Chang, J. Im, and G.-C. Cho, "Geotechnical engineering behaviors of gellan gum biopolymer treated sand," *Can. Geotech. J.*, vol. 53, no. 10, pp. 1658–1670, 2016. <https://doi.org/10.1139/cgj-2015-0475>
- [19] J. Krishna Leela and G. Sharma, "Studies on xanthan production from *Xanthomonas campestris*," *Bioprocess Eng.*, vol. 23, no. 6, pp. 687–689, 2000. <https://doi.org/10.1007/s004499900054>
- [20] A. K. Mohanty, M. Misra, and L. T. Drzal, "Sustainable bio-composites from renewable resources: Opportunities and challenges in the green materials world," *J. Polym. Environ.*, vol. 10, nos. 1–2, pp. 19–26, 2002. <https://doi.org/10.1023/A:1021013921916>
- [21] I. Chang, A. K. Prasadhi, J. Im, H.-D. Shin, and G.-C. Cho, "Soil treatment using microbial biopolymers for anti-desertification purposes," *Geoderma*, vols. 253–254, pp. 39–47, 2015. <https://doi.org/10.1016/j.geoderma.2015.04.006>
- [22] I. Chang, M. Jeon, and G.-C. Cho, "Application of microbial biopolymers as an alternative construction binder for earth buildings in underdeveloped countries," *Int. J. Polymer Sci.*, vol. 2015, Art. no. 326745, 2015. <https://doi.org/10.1155/2015/326745>
- [23] E. H. Oelkers and D. R. Cole, "Carbon dioxide sequestration: A solution to a global problem," *Elements*, vol. 4, no. 5, pp. 305–310, 2008. <https://doi.org/10.2113/gselements.4.5.305>
- [24] Z. Ali, M. Y. Fattah, and A. Al-Gharbawi, "Strength and compressibility characteristics of clay treated by pectin biopolymer," *Transp. Infrastruct. Geotech.*, vol. 12, Art. no. 158, 2025. <https://doi.org/10.1007/s40515-025-00620-w>
- [25] A. M. Al-Mahbashi, A. Shaker, and A. Almajed, "Using biopolymers to control hydraulic degradation of natural expansive-clay liners due to fines migration: Long-term performance," *Polymers*, vol. 18, Art. no. 272, 2026. <https://doi.org/10.3390/polym18020272>
- [26] T. A. Abd, M. Y. Fattah, and M. F. Aswad, "Strengthening of soft soil using carboxymethyl cellulose biopolymer," in *Proc. 2nd Int. Conf. Al-Esraa Univ. College Eng. Sci. (ICAUC_ES 2021)*, Baghdad, Iraq, Nov. 3–4, 2021, *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 961, Art. no. 012039, 2022. <https://doi.org/10.1088/1755-1315/961/1/012030>

- [27] J. E. McDonald, D. J. Rooks, and A. J. McCarthy, "Chapter nineteen—Methods for the isolation of cellulose-degrading microorganisms," in *Methods in Enzymology*, vol. 510. Amsterdam, The Netherlands: Academic Press, 2012, pp. 349–374. <https://doi.org/10.1016/B978-0-12-415931-0.00019-7>
- [28] I. Chang, M. Lee, A. T. P. Tran, S. Lee, Y.-M. Kwon, J. Im, and G.-C. Cho, "Review on biopolymer-based soil treatment (BPST) technology in geotechnical engineering practices," *Transp. Geotech.*, vol. 24, Art. no. 100385, 2020. <https://doi.org/10.1016/j.trgeo.2020.100385>



Influence of Skirt Length and Foundation Size on the Bearing Capacity of Circular Foundations Resting on Sandy Soil

Kawther Y. H. Al-Soudany^{1*} , Nahla M. Salim² , Luay Y. Hussein¹ 

¹ College of Engineering, University of Technology-Baghdad, Baghdad, Iraq.

² Department of Civil Engineering, College of Engineering, Al-Naji University, Baghdad, Iraq.

Article Info	ABSTRACT
Received: 14 June 2026 Revised: 13 Sep. 2026 Accepted: 21 Sep. 2026 Available online: 30 September 2026 Keywords: Skirted foundations; Bearing capacity; Settlement; Sandy soil; Soil confinement; Foundation diameter; Skirt length	Skirted foundations are an appropriate ground-improvement method for improving the performance of shallow foundations in sandy soils. This paper reports an experimental study on the effect of the skirt length and foundation size on the performance of circular foundations under vertical loading on medium-dense dry sand. Six laboratory model tests were made, of which two were unskirted and four were skirted foundations. Two (2) different diameters of circular footings, 60 mm and 90 mm, were tested with two different lengths of the footing skirts (L/D), 0.5 and 1.0. Terzaghi's criterion, in which the settlement is 10% of the footing diameter, has been used to determine the ultimate bearing capacity. The results showed that skirts significantly improved the load-settlement response, increased foundation stiffness, and increased ultimate bearing capacity. The ultimate load for the footing of diameter 60 mm was increased from 0.167 to 0.304 kN, which is about 82% increase when the footing is skirted with $L/D = 1.0$. The same trend applied to the 90 mm diameter footing, where the ultimate load went from 0.343 to 0.677 kN, which is about 97% improvement. The bearing capacity of foundations with $L/D = 0.5$ increased by 29% and 43% for footing diameters of 60 mm and 90 mm, respectively. The experimental results also showed that as the skirt increased in length, the settlement decreased, and the failure mechanisms were more stable and deeper due to the increased soil confinement and passive resistance along the walls of the skirts. Further, all skirts yielded higher failure loads with larger foundation diameters. The study has verified that the length of skirts and foundation size are important parameters that control the performance of circular skirted foundations on sandy soils. The application of skirts is an effective and cost-efficient way to increase bearing capacities, decrease settlement, and enhance shallow foundation stability.

1. Introduction

Shallow foundation performance is mainly influenced by soil's bearing capacity and settlement characteristics. Bulldozing over loose or weak soils can cause structures to have excessive settlement and insufficient load-bearing

capacity, posing serviceability and safety concerns. Such issues can be addressed with deep foundations but can be costly, time-consuming, and impactful to the environment. Thus, there has been a growing interest in geotechnical engineering on alternative ground improvement methods to increase the performance of shallow foundations.

Of these methods, skirted foundations have proven to be a practical as well as cost-effective alternative. A skirted foundation is a traditional footing with vertical or sloping skirts around the periphery of the foundation that extend into the soil and create a confined soil/footing system. This confinement helps to minimize lateral soil movement, enhance embedment depth, and alter the mode of failure, leading to increased bearing capacity and reduced settlement. Skirted foundations were originally designed for offshore structures like suction caissons, subsea systems, and offshore wind turbines but are also being used in onshore structures such as tanks, bridges, and industrial facilities, where they offer high load resistance, stability, and scour protection.

Skirted foundations have consistently been shown to provide improved performance in previous studies. Soil confinement effects on stress distribution and load transfer mechanisms were identified by Gourvenec and Randolph [1] with marked increases in bearing capacity and reduction in settlement. Different failure modes were found by Schneider and Senders [2], who finally found that with deeper penetration of the skirts, the failure surfaces will be deeper and more stable.

Experimental investigations by Tripathy [3] have reported significant improvements in load-carrying capacity for longer skirts and higher soil density, as well as Mahmood et al. [4] who saw an improvement in gypseous soils with deeper failure mechanism.

Moreover, Parmar and Patel [5] have highlighted that the geometry of the skirt, embedment depth and its inclination play a key role in the behavior of the foundation in cohesionless soils. Singh et al. [6] also verified the benefits of skirt depth on settlement and bearing capacity of the foundation, and those of inclined skirts were found to be better because of better confinement.

These results are summarized in recent review studies (2024-2025) which have confirmed that skirting foundations offer significant improvements in both bearing capacity, settlement control and stability under different loading conditions. These studies also indicate that

effective performance is achieved with a skirt length/width ratio between 1:1 and 2:1.

Although much research has been conducted, one of the most important issues regarding the behaviour of circular skirted foundations is the combined effect of foundation size and skirt length, especially in the case of vertical loadings in dry sandy soils. The majority of previous studies have examined geometric parameters individually, and have only had a few studies that examined interaction effects between geometric parameters.

This experimental study is therefore carried out to investigate the behavior of circular skirted foundations resting on dry sand under vertical load with special reference to the interaction effects of foundation diameter and skirt length on the ultimate bearing capacity and settlement characteristics of circular foundations. The results are expected to help in gaining better understanding of skirt-soil interaction and provide better design practices in geotechnical engineering.

2. Failure Modes in Soil

The maximum load that the foundation can bear when the stresses generated in the soil under the foundation reach the shear strength of the soil and cause soil failure is what is called the ultimate bearing capacity of the foundation. Soil density, compressibility, strength properties, and foundation embedment ratio (D_f/B) are the most important factors influencing the mode of failure. There are three main failure modes: general shear, local shear and punching shear.

The shear failure, which is normally called general shear failure, happens in dense sand and stiff clay and is typically manifested by well-defined failure surfaces that continue upward from the edge of the foundation to the ground surface. In this mode, there is usually a significant load-settlement peak and soil heaving. Local shear failure is the case for medium-density and consistency soils, where the failure surface is not complete, and larger settlements take place prior to ultimate failure. Punching shear failure is normally seen in very loose sands and soft clays where the foundation has minimal lateral movement and no well-defined shear surfaces to the ground surface.

Classical bearing capacity theories generally assume that a general shear failure occurs amongst these failure mechanisms. The skirts of skirted foundations alter the failure mechanism by confining the soil and pushing the failure surface deeper into the soil. Thus, the bearing capacity is increased, and the settlement is reduced when compared to a traditional shallow foundation.

3. Determination of Ultimate Bearing Capacity from Load–Settlement Curves

The interpretation of ultimate bearing capacity from load–settlement test results is an important aspect of foundation analysis. Several criteria have been proposed to define the ultimate load, particularly in cases where a clear failure point is not observed.

According to Terzaghi [7], the ultimate bearing capacity may be defined as the pressure corresponding to a settlement equal to 10% of the foundation width or diameter. This criterion has been widely adopted in laboratory and field investigations of shallow foundations. Another commonly used approach is the tangent intersection method, in which the ultimate load is determined from the intersection of two tangents drawn to the initial and final portions of the load–settlement curve.

Different interpretation methods may yield different values of ultimate bearing capacity. Therefore, it is important to adopt a consistent criterion when comparing experimental results. Lutenegeger and Adams [8] evaluated several interpretation methods using model footing tests on sand and concluded that the bearing capacities obtained from the 10% settlement criterion are generally higher than those obtained using the tangent intersection method. Figure 1 illustrates typical methods used to determine ultimate bearing capacity from load–settlement relationships.

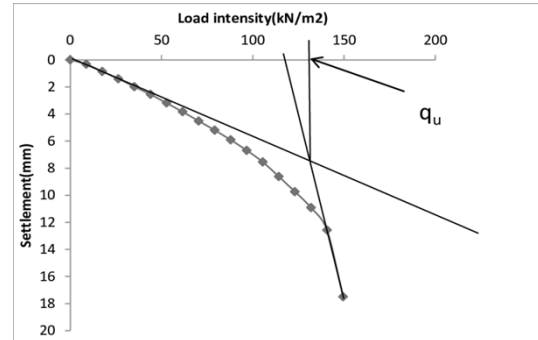
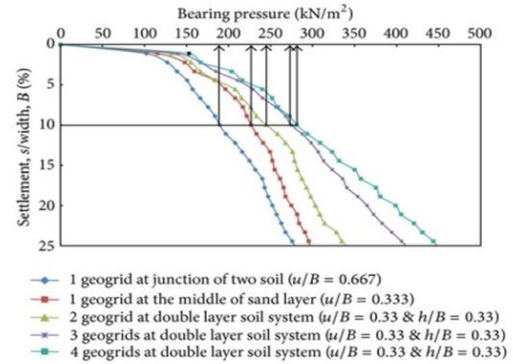


Figure 1. Defining ultimate bearing capacity of shallow foundation from load-settlement test results by using different methods (after Cerato, 2005) [9]

4. Materials and Methods

4.1 Experimental Program

An experimental study was conducted to investigate the behavior of circular skirted foundations resting on dry sand and subjected to vertical loading. A total of six model tests were performed, including two tests on unskirted foundations used as reference cases and four tests on skirted foundations. The investigated variables were foundation diameter and skirt length.

Two circular foundation diameters of 60 mm and 90 mm were considered. For each diameter, it was observed the skirt lengths of 0.5D and D (where D is the foundation diameter). The load–settlement response and ultimate bearing capacity for each foundation configuration was evaluated and compared.

4.2 Materials

4.2.1 Sand

All the experiments were performed on Karbala sand. The sand was cleaned, dried in an oven, and sieved through a 2 mm sieve before testing. Using the Unified Soil Classification System (USCS), the sand was determined to be

poorly graded sand (SP). The sand bed was prepared with a relative density of 60%, which is considered a medium-dense condition.

The engineering properties of the sand were obtained from laboratory investigations such as sieve analysis, specific gravity test, and direct shear test. The main properties of the sand are summarized in Table 1.

Table 1. Physical properties of the tested sand.

Property	value	Specification
D10	0.14 mm	ASTM D 422 [10]
D30	0.23 mm	
D50	0.36 mm	
D60	0.41 mm	
Coefficient of uniformity (C_u)	2.93	ASTM D 854 [11]
Coefficient of curvature (C_c)	0.92	
Specific gravity (G_s)	2.64	
Angle of internal friction (ϕ)	34°	
Maximum dry unit weight (γ_{dmax})	17.5 kN/m ³	ASTM D 2049-69 [13]
Minimum dry unit weight (γ_{dmin})	14.2 kN/m ³	ASTM D 4254-00 [14]
Relative density of sand during test (D_r)	60 %	-----
Dry unit weight in test (γ_d)	16.02 kN/m ³	-----
Saturated unit weight (γ_{sat})	19.76 kN/m ³	-----

4.3 Foundation Models

Circular steel foundation models with diameters of 60 mm and 90 mm and a thickness of 20 mm were used throughout the testing program.

4.3.1 Skirts

The skirts were fabricated from aluminum cylinders open at both ends. Two skirt lengths were considered, namely 0.5D and D. The skirt diameter was equal to the corresponding foundation diameter, while the skirt thickness was maintained constant at 5 mm for all tests. The skirts were rigidly connected to the foundation models using bolts to ensure monolithic behavior during loading.

4.4 Experimental Setup

The test was performed in a rigid steel container with dimensions of 600 mm × 300 mm (plan) and 350 mm (depth). The size of the containers was chosen to reduce edge influences when loading. The foundation models were subjected to concentric loading using a vertical loading system and settlements were measured using a dial gauge of accuracy 0.01 mm.

4.4.1 Sample Preparation and Testing Procedure

The sand bed was formed in the test container by a layer-by-layer deposition method to obtain a relative density of 60%. The sand was laid in 6 equal layers and lightly compacted to make sure that the soil mass was even. The surface of the soil was carefully levelled after the preparation, and the foundation model was placed.

In the case of the reference tests, the foundation was directly installed on the sand surface. In the case of skirted foundation tests, the skirt was inserted vertically into the excavated sand and firmly attached to the foundation. It was noted that care was taken in the installation to minimize soil disturbance and to have a constant density condition for all tests.

The loads were applied sequentially via a loading rod located in the centre of the specimen, which transmits vertical loading. The loads were applied sequentially via a loading rod at the centre of the specimen that transmits vertical loading. After load increment stabilization, settlement readings were taken. This loading process was continued until a clear failure condition was achieved or until the settlement amount went beyond a pre-defined failure condition. To prevent

the footing from rotating and distribute the stress evenly below the footing, concentric loading was used throughout the test program.

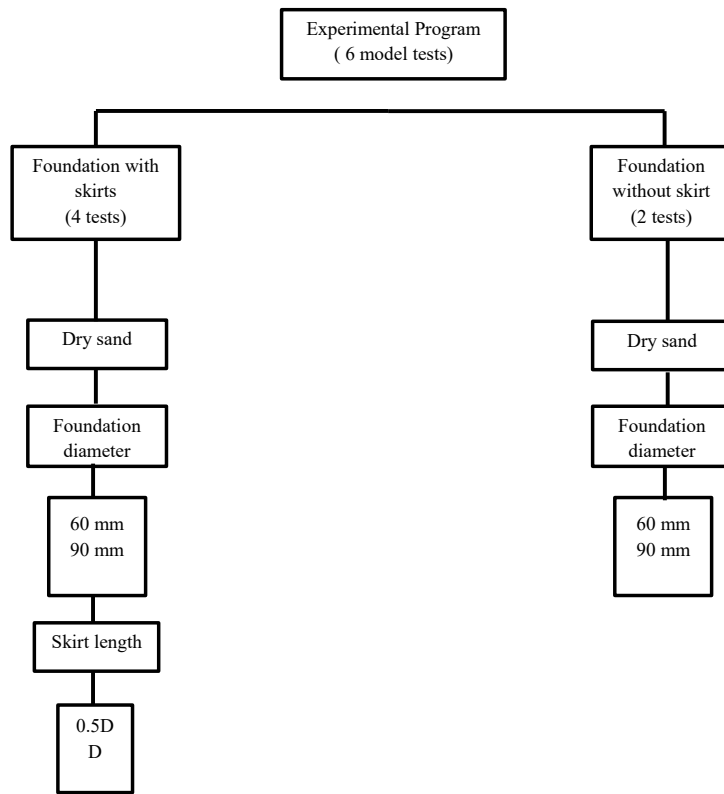


Figure 2. Flowchart for testing program

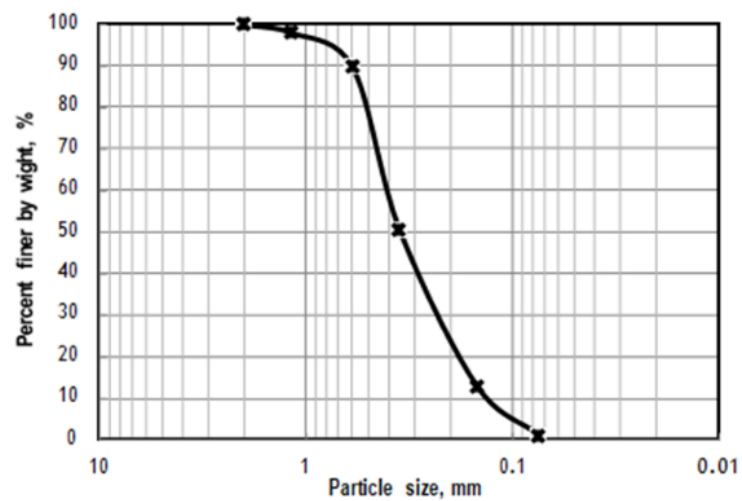


Figure 3. Particle size distribution of the sand

4.4.2 Foundation Models and Skirt Configuration

The circular steel footing models were constructed in sizes 60 mm and 90 mm with a constant thickness of 20 as presented in Figure 4).



Figure 4. Foundation used

4.4.3 Skirt Configuration

The effect of soil confinement in a foundation was studied using aluminum skirts. The skirts were made in the shape of hollow cylindrical pieces of length $0.5D$ and D (where D is the footing diameter). The two footing diameters, 60 mm and 90 mm, were investigated, and the corresponding skirt diameters were chosen to correspond with the footing diameters. The thickness of the skirt was kept at 5 mm in all tests.

The skirts were firmly connected to the skirts' perimeter using bolts to provide the composite action between the skirts and footings under loading. This allowed the limited soil under the footing to participate in load transfer, increasing the bearing capacity and decreasing the settlement. (Figure 5)



Figure 5. Skirt Configuration used in the present works

As shown in Figure 6, the skirts were securely fastened to the edge of the footing models using bolts, allowing the footing-skirt assembly to behave as a single unit throughout the loading process.



Figure 6. Skirted foundation models

5. Experimental Setup

An experimental program was carried out using a laboratory-scale testing system, which was developed to investigate vertical loading response of skirted foundations. The apparatus consisted of a steel soil container, circular footing models, a raining apparatus of sand to reproduce specimens with control, and a vertical loading system as shown in Figure 7.



Figure 7. Test set-up

5.1 Soil Container

The soil container used was a rigid steel test tank of length 600 mm, width 300 mm and depth 350 mm. The thickness of steel plates used for constructing the tank was 4 mm. Uniform sand layers were obtained during the testing program by providing reference markings at 50 mm intervals.

5.2 Sand Bed Preparation

To achieve a uniform stress distribution in the soil mass and provide a stable base for the test tank, a 50 mm thick gravel layer was first laid at the base of the test tank. The sand sample was then processed in a calibrated layer-by-layer deposition process. The soil was laid in six layers of equal thickness (about 50mm); the target dry unit weight was 16.02 kN/m^3 . Using $\gamma_d, \text{ max} = 17.5 \text{ kN/m}^3$, γ_d ,

$\min = 14.2 \text{ kN/m}^3$, and $G_s = 2.64$, this dry unit weight corresponds to a calculated relative density of approximately 61%, consistent with the target $D_r = 60\%$. Preliminary calibration tests were performed to determine the placement process necessary to create a uniform density distribution of soil in the soil bed. The experimental results were repeatable and reliable by paying particular attention to deposition conditions, achieving the same layer thickness, and avoiding disturbances during specimen preparation.

5.3 Testing Procedure

A sand bed was prepared in the test tank by using a calibrated deposition procedure and giving a uniform relative density to the specimen depth. Once the desired density was reached, the surface of the sand was levelled carefully to ensure that a smooth and flat testing surface was created.

Vertical loading tests under a series of different loading rates were carried out on circular foundations of diameters 60mm and 90mm. The footing was located in the middle of the test tank to reduce the boundary effect. Concentric load application was ensured by providing a recess in the middle of the surface of the footing to accommodate the loading rod and to ensure the rod is aligned with the centre of the footing during testing.

Two types of foundation were studied: Unskirted and Skirted foundations. The footing in the reference tests was installed on the pre-packed sand surface. The aluminum skirts were firmly attached to the footing with four bolts each, above the foundation length of D and $0.5D$ for skirted tests, creating a single composite structure. A skirted assembly was then carefully placed in the sand excavated vertically without disturbing the adjacent soil and at the desired relative density.

Load was applied incrementally using calibrated weights. Each increment was maintained until the measured settlement was considered stabilized, after which the settlement reading was recorded. The dial gauge had an accuracy of 0.01 mm and a range of 50 mm. The test continued until the load–settlement response reached the predefined settlement criterion or a clear failure response was observed.

The load was applied in sequential increments, with each increment corresponding to

approximately 10% of the estimated ultimate bearing load. Each load increment was maintained for approximately 30 min. Settlement readings were taken after the settlement response had stabilized. Settlement was considered stabilized when the rate of settlement was less than 0.01–0.02 mm/min (approximately 0.6–1.2 mm/h). This loading and stabilization procedure was applied consistently throughout the testing program.

Special emphasis was placed on keeping the soils consistent and not disturbing the soil during installation of the footings throughout the testing program. In addition, careful attention was made to ensure that the footing was loaded concentrically, and that the measured response was the correct response of the foundation-soil system to vertical loading.

6. Results and Discussion

6.1 Overview

A series of laboratory model tests was performed to evaluate the performance of circular skirted foundations in medium-dense dry sand under vertical loading. The experimental program comprised six tests, one of which were reference test on an unskirted foundation, and the others were tests on skirted foundations of various lengths. The main goal of the research was to determine the effects of skirt length and foundation diameter on the response of the foundation system in terms of load-settlement behavior, ultimate bearing capacity, and settlement behavior.

The results in this section give a comparative evaluation of the 60 mm and 90 mm diameters with skirt length/diameter ratios of 0.5 and 1.0. Skirted foundations are compared with the responses of traditional shallow foundations to measure the benefits of soil confinement. To quantify the improvement achieved through soil confinement.

6.2 Failure Criterion

The ultimate bearing capacity (q_u) of the tested foundations was calculated using the settlement criterion suggested by Terzaghi (1943) where the failure load is taken as the settlement of the footing is 10% of the footing diameter. This criterion is commonly used in model foundation studies and offers a convenient and uniform means

of judging the performance of various foundation types.

Thus, the ultimate load (Q_u) for each test was defined as the applied load at a footing settlement of $0.1D$, where D is the footing diameter.

6.3 Load–Settlement Response

The load–settlement characteristics of circular foundations were then examined using the results of six model tests performed under vertical loading in medium-dense dry sand ($RD = 60\%$). The experimental set-up comprised unskirted foundations ($0D$) and two different skirt lengths, $0.5D$ and $1D$, on footing diameters of 60 mm and 90 mm, and this allowed an assessment of the effect of skirt length and footing size on the performance.

The load–settlement curves (Figures 8 and 9) clearly show that the stiffness and load-carrying capacity of a skirted foundation are much superior to those of an unskirted foundation. The results

show a significant decrease in settlement from the same applied load. At a representative load level of $\sim 40\text{kg}$, for example, the settlement reduced from $\sim 10\text{--}12\text{mm}$ ($0D$) to $6\text{--}8\text{mm}$ ($0.5D$) and further to $\sim 4\text{--}5\text{mm}$ ($1D$). It is seen to improve progressively with increasing skirt length. The slope of the curve of the load–settlement curve increases with increasing skirt penetration, indicating increased initial stiffness and load transfer characteristics.

The improvement is explained by the confinement effect of the skirts that control the lateral movement of the soil, thus leading to deeper failure mechanisms. Therefore, the greater the volume of soil mobilized, the higher the bearing capacity and the less the soil will deform under the applied load. Also, the effect of footing diameters is observed, as the load resistance will consistently be higher for the 90 mm footing under similar skirt conditions as compared to the 60 mm footing, showing the pronounced scale effect on the overall footing response.

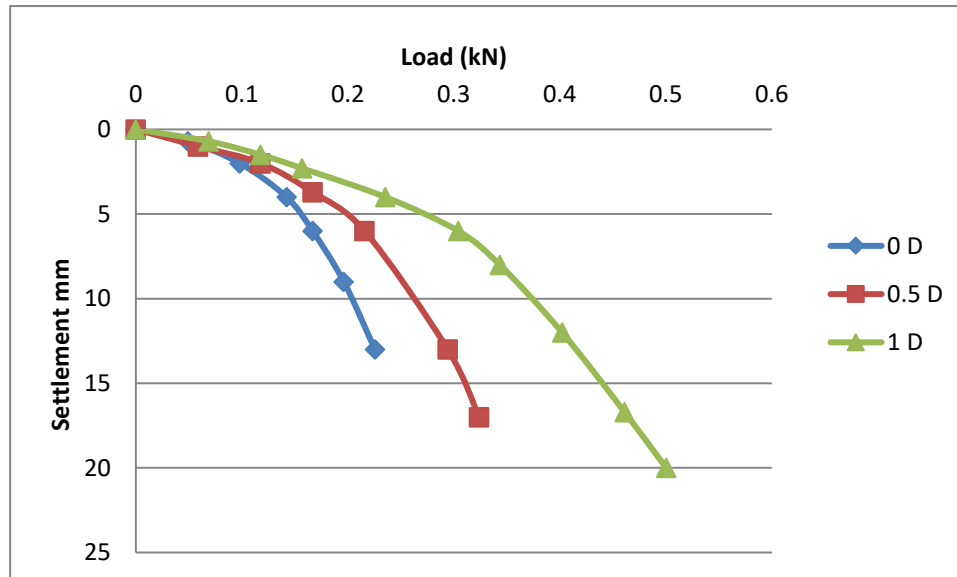


Figure 8. Load vs. foundation settlement relationship for the foundation 60 mm in diameter with skirt resting on dry sand

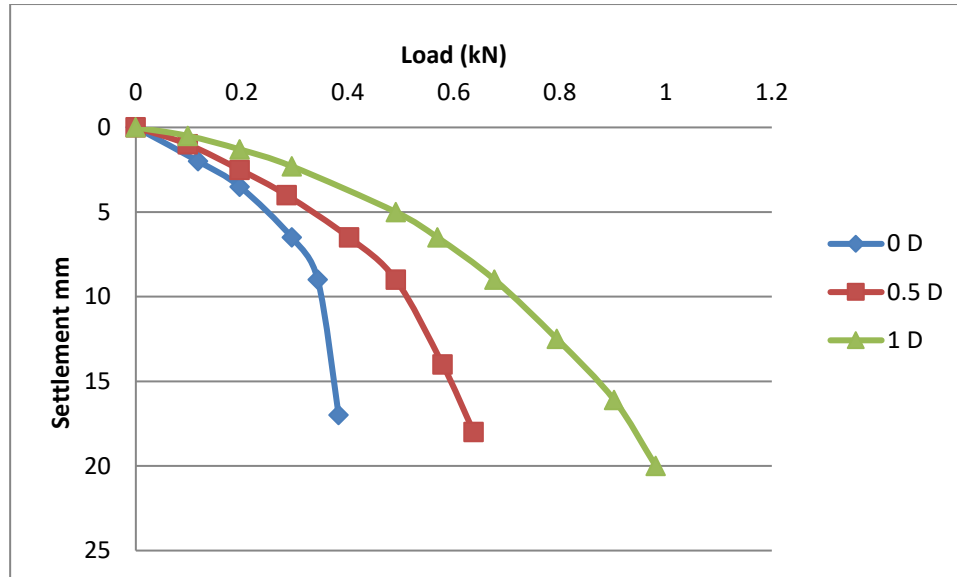


Figure 9. Load vs. foundation settlement relationship for the foundation 90 mm in diameter with skirt resting on dry sand

6.4 Effect of Skirt Length

Experimental results show the effect of skirt length on the foundation performance. In both footing diameters, the longer the skirts were, the higher the load-carrying capacity and the lower the settlement value.

The longer the skirts, the more soil they hold and the deeper the effective embedment depth of the foundation. This results in increased passive resistance of skirt walls and the failure surface moving to deeper and more competent soils. Hence, the foundations with longer skirts were found to have higher stiffness and ultimate loads than the shorter skirts.

This advantage of skirt length was seen consistently for both the diameters of the footing and it is demonstrated that the penetration depth of the skirts is one of the governing parameters that determines the behavior of skirted foundations on sandy soils. From this it is clear that the use of skirts has a marked improvement in the performance of the foundation, especially the load carrying capacity and settlement reduction. The improvement is greater with longer skirts and larger foundation diameters, demonstrating the positive effect of soil confinement and greater effective embedment depth. El Wakil [15] reported significant improvement on the bearing capacity of skirted foundation on sandy soils.

It shows that ultimate loads are significantly increased by the presence of skirts, when comparing load–settlement curves for the two sets of footings at the failure settlement criterion (10% of footing diameter). The unskirted footing failed with an ultimate load of 0.167 kN, whereas the foundation with a skirt length-to-diameter ratio (L/D) of 1.0 was able to sustain an ultimate load of 0.304 kN for the 60 mm diameter footing. In a similar way, for the 90 mm diameter footing, the ultimate load rose from 0.343 to 0.677 kN when L is the same as the diameter of the footing.

The largest increase was recorded for the 90 mm diameter foundation of an L/D ratio of 1.0 where the ultimate load increased by approximately 97% compared to the same unskirted foundation. The reasons for this sizeable improvement are the higher confinement of the soil under the footing and the activation of additional passive resistance along the skirt walls that cause a more deeply developed and stable failure mechanism.

The ultimate load increases for the different skirts as compared with the unskirted foundations ($L/D = 0$) are summarized in Tables 2 and 3.

The performance improvement of the skirted foundations is mainly due to the confinement of the soil inside the skirts. This confinement restricts the lateral soil movement, enhances the passive resistance of the skirt walls, and encourages a

deeper load transfer mechanism. Hence, the foundation has higher bearing capacity and a lesser settlement than the unskirted foundation.

Table 2. Percent increase in failure load for foundation skirt in dry sand.

L/D ratio	% increase in failure load for different foundation diameter	
	60 mm	90 mm
0.0	-	-
0.5	29	43
1.0	82	97

Table 3. Summary of ultimate load and bearing pressure for all tested configurations.

D (mm)	L/D	Q_u (kN)	q_u (kPa)
60	0	0.167	59.0
60	0.5	0.216	76.3
60	1.0	0.304	107.6
90	0	0.343	54.0
90	0.5	0.491	77.1
90	1.0	0.677	106.4

The effect of the skirt length on the skirted foundations' behavior was studied through a series of model tests, with two different skirt length-to-diameter ratios ($L/D = 0.5$ and 1.0) for each footing diameter. The experimental results were evaluated by load-settlement relationship and ultimate bearing capacity to quantify the contribution of the increase in the skirt penetration length to foundation performance. The corresponding results are shown in Figure 10).

The findings show that there is a strong increasing trend in the ultimate bearing capacity with an increase in skirt length for both footing diameters. The failure loads of the foundations with $L/D = 1.0$ were higher than those of the foundations with $L/D = 0.5$ in all cases, and were greater than those of the unskirted foundations of the same L/D . This is said to be caused by the higher soil confinement and deeper load transfer mechanism achieved with deeper penetration depths of skirts.

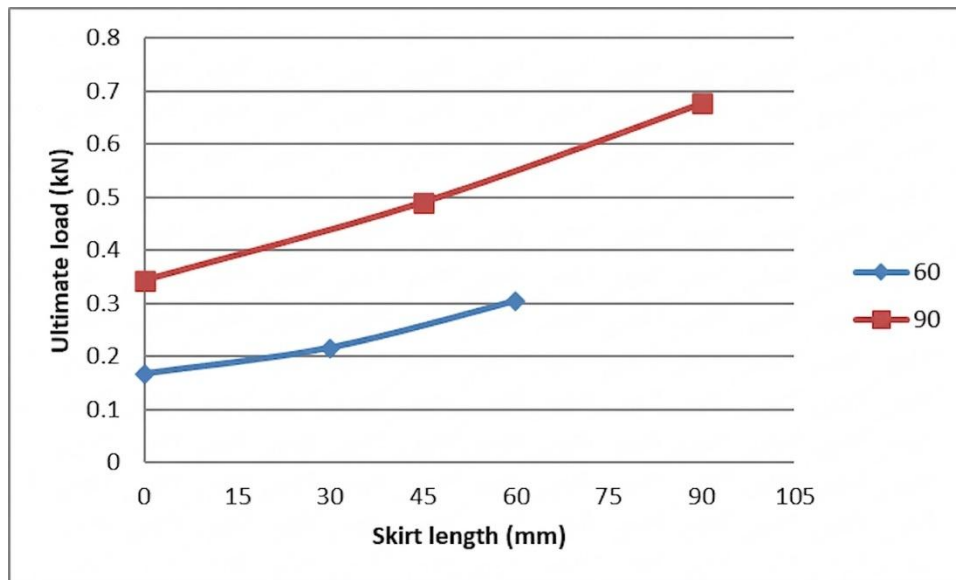


Figure 10. Shows the variation of failure load with respect to skirt foundation length in dry sand.

6.5 Effect of Foundation Size

In the Figure 11) Foundation diameter increased the total ultimate load in every tested skirt configuration. However, comparison of total load alone can be misleading because the footing area increases with D^2 . The unskirted 90 mm

footing carried 0.343 kN compared with 0.167 kN for the 60 mm footing, while the corresponding bearing pressures were 54.0 and 59.0 kPa. For $L/D = 0.5$, the pressures were 77.1 and 76.3 kPa, and for $L/D = 1.0$ they were 106.4 and 107.6 kPa for the 90 and 60 mm footings, respectively.

These results indicate that the increase in total load with foundation size is strongly associated with the larger loaded area. After normalization by footing area, the skirted cases show similar ultimate bearing pressures for the

two diameters. Therefore, the present six tests do not justify a broad claim that foundation diameter alone increases unit bearing capacity.

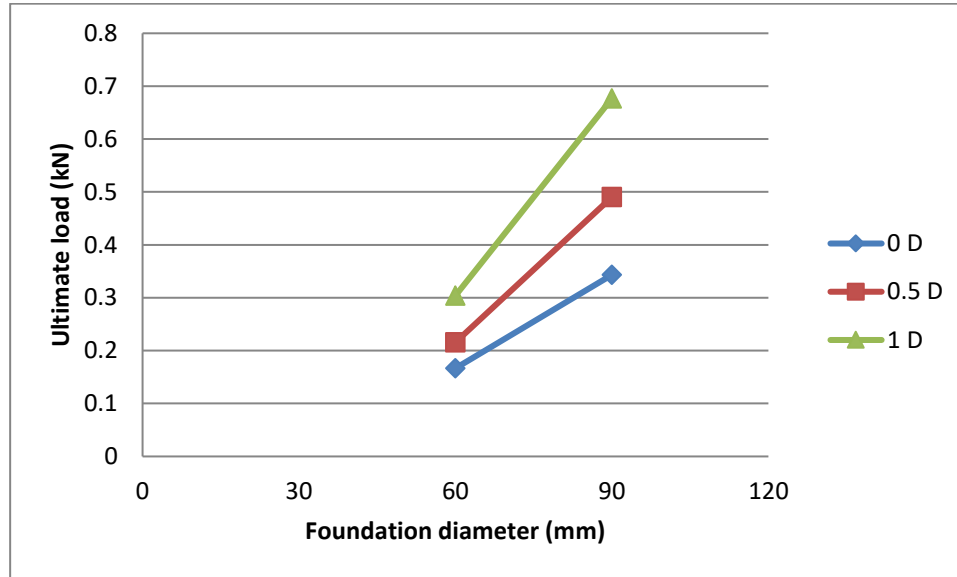


Figure 11. Failure load vs. foundation size in dry sand

7. Conclusions

An experimental study was carried out to examine the response of circular skirted foundations subjected to vertical loading in medium-dense dry sand. Six model tests were conducted in laboratories to investigate the effect of foundation diameter and skirt length on load-settlement response and ultimate bearing capacity. From the experimental results, the following conclusions can be drawn:

Skirts significantly enhanced the performance of shallow foundations by enhancing the ultimate bearing capacity and decreasing the foundation settlement. The better improvement was the longer and wider the skirts, and the greater the footing diameter. At an L/D ratio of 1.0, the carrying capacity increased up to 82% and 97% for the 60 mm and 90 mm diameter footings, respectively.

The skirted foundations were found to be a very effective and practical method for increasing the bearing capacity of foundations on sandy soils. The improvement was determined to be most dependent on the length of the skirt, the size of the

foundation, and the nature of the soil upon which it is placed.

The vertical settlement of the tested foundations was reduced by the presence of skirts due to the confinement of soil under the footing and the formation of a deeper load-transfer mechanism. For buildings where settlement control is an important design consideration, skirted foundations might be a viable option.

The ultimate bearing capacity increased with increasing skirt length for a given diameter of footing. The maximum performance was obtained for $L/D = 1.0$, which means that better soil confinement is achieved at higher penetration depths of the skirts and more passive resistance is mobilized.

It was concluded that the foundation diameter had a significant effect on the load-carrying capacity. For all other skirt combinations, larger footings had higher ultimate loads than smaller footings. The 90 mm diameter footing with a skirt length the same as the footing diameter gave the highest bearing capacity.

Overall, outcomes indicate that the use of skirts can significantly improve the performance of shallow foundations on sandy soils by increasing the foundation bearing capacity, decreasing the foundation settlement, and improving the foundation stability by soil confinement.

Acknowledgements

The authors express their appreciation to the University of Technology - Iraq for academic support for the research efforts.

Conflict of interest

The authors declare no conflicts of interest concerning this research.

Funding

No funding was received for conducting this study.

Author Contribution

K.Y.H. Al-Soudany: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. N.M. Salim: Writing – review & editing, Validation, Supervision. L.Y. Hussein: experimented, wrote the paper, and worked out almost all of the technical details

AI Declaration Statement

The authors confirm that the manuscript has been written without the assistance of generative AI or AI-based writing tools.

Data availability

Data will be made available on request

References

- [1] S. Gourvenec and M. F. Randolph, "Consolidation beneath circular skirted foundations," *Int. J. Geomech.*, vol. 10, no. 1, pp. 22–29, 2010. [https://doi.org/10.1061/\(ASCE\)1532-3641\(2010\)10:1\(22\)](https://doi.org/10.1061/(ASCE)1532-3641(2010)10:1(22))
- [2] J. A. Schneider and M. Senders, "Foundation design: A comparison of oil and gas platforms with offshore wind turbines," *Mar. Technol. Soc. J.*, vol. 44, no. 1, pp. 32–51, 2010. <https://doi.org/10.4031/MTSJ.44.1.5>
- [3] S. Tripathy, "Load carrying capacity of skirted foundation on sand," Ph.D. dissertation, National Institute of Technology, Rourkela, India, 2013.
- [4] M. R. Mahmood, M. Y. Fattah, and A. Khalaf, "Experimental study on bearing capacity of skirted foundations on dry gypseous soil," *Int. J. Civ. Eng. Technol.*, vol. 9, no. 10, pp. 1910–1922, 2018.
- [5] S. Parmar and R. Patel, "Bearing capacity of isolated square skirted foundation on cohesionless soil: An experimental and analytical study," *J. Adv. Geotech. Eng.*, vol. 4, no. 2, pp. 1–11, 2021.
- [6] S. P. Singh, S. Kumar, and S. Sarkar, "Numerical analysis of skirted foundation on sand for load–displacement behaviour," in *Proc. Indian Geotech. Conf. 2022*, vol. 2. Singapore: Springer Nature Singapore, 2024, pp. 251–263. https://doi.org/10.1007/978-981-97-1741-5_22
- [7] K. Terzaghi, *Theoretical Soil Mechanics*. New York, NY, USA: John Wiley & Sons, 1943.
- [8] A. J. Lutenecker and M. T. Adams, "Bearing capacity of footings on compacted sand," in *Proc. Int. Conf. Case Histories Geotech. Eng.*, St. Louis, MO, USA, Mar. 9–12, 1998, pp. 1216–1224.
- [9] A. B. Cerato, "Scale effect of shallow foundation bearing capacity on granular material," Ph.D. dissertation, Dept. Civil Environ. Eng., Univ. Massachusetts Amherst, Amherst, MA, USA, 2005.
- [10] ASTM D422-63, *Standard Test Method for Particle-Size Analysis of Soils*. West Conshohocken, PA, USA: ASTM International, 2006.
- [11] ASTM D854-23, *Standard Test Methods for Specific Gravity of Soil Solids by the Water Displacement Method*. West Conshohocken, PA, USA: ASTM International, 2006.
- [12] ASTM D3080-04, *Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions*. West Conshohocken, PA, USA: ASTM International, 2006.
- [13] ASTM D2049-69, *Standard Test Method for Relative Density of Cohesionless Soils*. West

- Conshohocken, PA, USA: ASTM International, 1969.
- [14] ASTM D4254-16, *Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density*. West Conshohocken, PA, USA: ASTM International, 2006.
- [15] A. Z. El-Wakil, "Horizontal capacity of skirted circular shallow footings on sand," *Alex. Eng. J.*, vol. 49, no. 4, pp. 379–385, 2010.
<https://doi.org/10.1016/j.aej.2010.07.003>

