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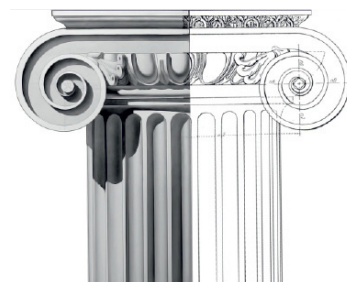


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BREATHING FAÇADES AS CLIMATE-RESPONSIVE STRATEGIES: CASE STUDIES ACROSS DIVERSE CLIMATIC CONTEXTS

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Abstract

Introduction. This study evaluates the effectiveness of breathable façades as an innovative architectural solution that contributes to ensuring continuous ventilation, improving indoor air quality, reducing pollutant accumulation, and decreasing energy consumption in diverse climatic and geographical contexts. **Purpose of the study.** The study aims to examine the use of these façades in different environments and determine their flexibility and effectiveness. **Methods.** A descriptive and comparative analytical approach was adopted, examining 42 global and regional models, spanning continents and diverse climates. The models were classified according to four principal criteria: geographical location, building materials, design systems, and ventilation patterns, with tables used to illustrate the most common patterns. **Results.** The findings indicate that global models emphasise diverse solutions that enhance ventilation and air quality, while the regional models are distinguished by the use of low-cost, environmentally sustainable materials, demonstrating flexibility and effectiveness. These results confirm the environmental and functional efficacy of breathable façades across varied climatic conditions.

Keywords: breathing façades, natural ventilation, climate adaptation, indoor air quality, comparative analysis, sustainable architecture.

Introduction

Natural ventilation is one of the most important architectural strategies aimed at improving the indoor environmental quality of buildings (Plazas and de Tejada, 2024). It contributes to air renewal and reduces the accumulation of pollutants and harmful substances within spaces, which directly impacts the health and comfort of users (Levie et al., 2014; Stabile, Dell'Isola, Russi, Massimo and Buonanno, 2017; Pesic, Calzada and Alcojor, 2018; Rodrigues, Santos, Gomes and Duarte, 2019). Research demonstrates that natural ventilation can significantly reduce energy consumption by reducing reliance on mechanical air conditioning systems, making it one of the essential solutions for achieving energy efficiency in buildings (Yang and Clements-Croome, 2020). From this perspective, breathing façades have emerged as an innovative architectural solution, allowing air to continuously circulate through their layers to provide effective natural ventilation (Shalaby, Abo El Enein, Saif, and El Gheznawy, 2020).

This approach is an extension of ancient architectural traditions, such as mashrabiya in Islamic architecture or wooden screens in Asian architecture, which were used to control light and air while maintaining privacy (Ashour, 2018). Breathing

façades are also directly linked to concepts of sustainability, not only through reduced energy consumption, but also through their ability to be manufactured from low-cost local materials such as stone, wood, and pottery, thus reducing the carbon footprint associated with transportation and production (Ulung, 2023). This opens the door to their application in a wide range of environments and climates (Farid, Ahmad, Raub and Shaari, 2016).

Despite the growing global interest in this type of façade, comparative studies examining the differences between global and regional models remain limited, particularly regarding their adaptability to diverse climatic conditions or the local materials used in their performance (Elghawaby, 2012).

Scope

This research examines breathing façades as a contemporary architectural strategy for improving the environmental performance of buildings by enhancing natural ventilation, reducing energy consumption, and minimising indoor pollutant accumulation, thereby improving air quality and user comfort. The scope of the study includes a comparative analysis of 42 global and regional models, categorised according to five main principal criteria: geographical location, climatic conditions,

climate adaptation, building materials, façade type, and building type. This diverse range of models was selected to provide a more comprehensive understanding of the flexibility of this technology and its adaptability to different environments. This approach enables the identification of similarities and differences in design and construction characteristics, as well as the evaluation of compatibility with sustainability requirements across diverse climatic contexts.

Objectives

This research aims to evaluate the effectiveness of breathing façades as a sustainable architectural solution through a comparative analysis of 42 global and regional case studies. The study focuses on evaluating the ability of these façades to improve natural ventilation and reduce energy consumption and pollutants as well as understanding how local materials and diverse design strategies can be employed according to different climatic conditions. Through this analysis, the study seeks to highlight similarities and differences between global and regional experiences, thereby clarifying the potential for broader application of this technology to achieve the principles of environmental and architectural sustainability.

Methodology

A set of integrated research methods was adopted to study breathing façades and analyse their impact on the environmental performance of buildings. The research began with a descriptive and analytical approach, collecting data from 42 global and regional models of breathable façades and categorising them according to five main criteria: geographical location, climate, building type, materials used, and architectural design. This categorisation enabled the

identification of architectural solution diversity and common patterns among the models, with a focus on the role of local materials in improving sustainability and optimising energy consumption.

Next, an inductive approach was applied to study each model individually, analysing how design elements and materials influence natural ventilation, pollutant accumulation, and energy efficiency. This detailed analysis contributed to drawing accurate conclusions about the effectiveness of each façade type in different environments.

Finally, a comparative approach was employed to evaluate the differences and similarities between global and regional models, focusing on design strategies, materials, and environmental characteristics. This analysis aimed to identify globally and locally applicable best practices and to understand how architectural solutions can be adapted to meet diverse climatic and functional needs, thereby enhancing the sustainability and efficiency of natural ventilation façades.

Historical Overview of Breathing Façades

Breathing façades are an extension of ancient architectural traditions that combine natural ventilation, climate mitigation, and privacy protection. They have evolved across different civilisations in various forms and materials. In the Islamic world, the mashrabiya (or roshan) is a prominent traditional example, where architects used perforated wood projecting from the façade to achieve natural ventilation, shade, and privacy (Ashour, 2018).

In India, the Jali system was used, consisting of stone screens (Fig. 1). These are perforated with intricate geometric patterns that allowed air to pass through and mitigated sunlight (Gupta et al., 2022). Similarly, in China, traditional buildings relied on



Fig. 1. Jali system In India

perforated wooden lattice screens, which served similar environmental and decorative functions (Yi, 2018)

In the 20th century, a modern model emerged in Brazil, based on the same traditional principles: Cobogó (Camacho et al., 2017; Miranda et al., 2019). Perforated or decorative concrete units were installed on façades to allow air to pass through (Fig. 2). This system represents an extension of mashrabiya structures (Vettorazzi et al., 2024) and uses modern materials suited to hot and humid climates (de Araújo and Bistafa, 2012).

Thus, Table 1 summarises the environmental characteristics of breathing façades across different civilisations. This historical sequence demonstrates that breathing façades are a universal concept that has evolved over the ages, relying on local materials and adapting to varying climatic conditions. This supports the primary objective of this research: to investigate effective and flexible solutions for natural ventilation, improving the environmental performance of buildings and reducing pollutants in modern architecture.

Case Studies of Breathing Façades

This section presents an analysis of selected breathing façade models, discussing the differences and similarities between their general information and façade key elements.

Selection Criteria for Case Studies

This research examines case studies that have employed breathing façades in buildings for several objectives, such as minimising pollution, enhancing indoor air quality, and optimising ventilation. The selected cases were categorised into global and regional models based on their geographical distribution to enable a systematic comparison of breathing façade application patterns across different regions.

Global models comprise projects selected from countries across multiple geographical regions worldwide, including Europe, Asia, North America, and Oceania. These models represent global trends in technological development, material use, and design strategies related to ventilated façades.

Regional models, in contrast, are limited to projects within a specific geographical area, such as the Middle East and North Africa (MENA) region. This allows for comparison of application

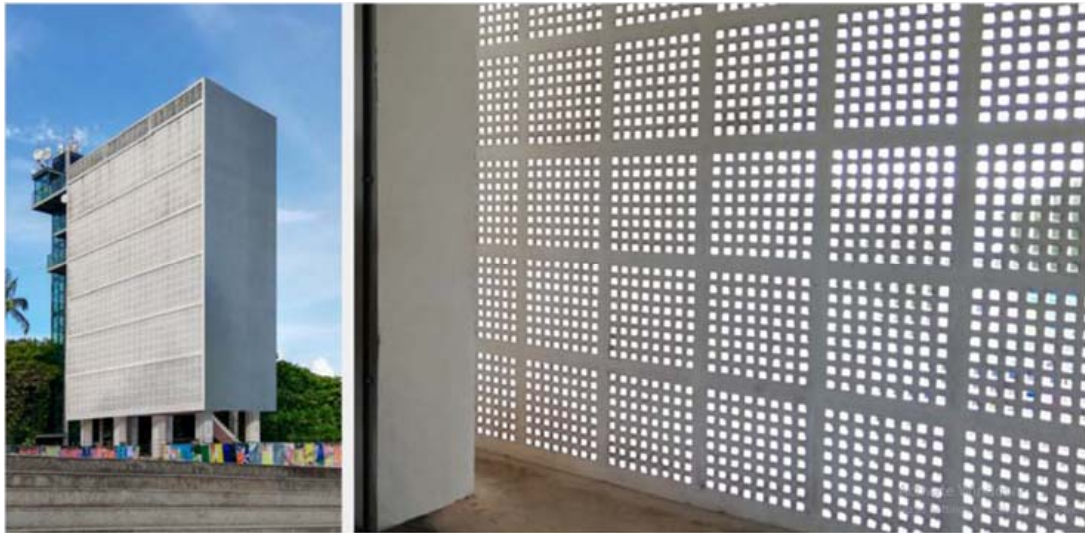


Fig. 2. Example of a cobogó building Caixa d'Água de Olinda, 1935

Table 1. Evolution of breathing façades across different civilisations

Culture/Country	Façade Type	Materials Used	Environmental Functions	Social/Additional Functions
Islamic World	Mashrabiya	Perforated Wood	Natural Ventilation, Climate Moderation, Shading	Privacy Protection, Decoration
India	Jali	Perforated Stone with Geometric Patterns	Ventilation, Sunlight Mitigation	Decoration, Privacy
China	Lattice Screens	Perforated Wood	Ventilation, Moderation	Moderation Decoration
Brazil	Cobogó	Perforated or Decorative Concrete	Ventilation, Natural Light, Heat Mitigation	Decoration, Privacy

patterns within a more homogeneous geographical context.

This comparative classification highlights the differences between global technological trends and regional application patterns. These differences can be explained by contextual characteristics of each region, such as prevailing construction practices, material availability, and local design and implementation considerations. To enhance the clarity of the case studies and increase the analytical value of the comparison, the buildings were first organised by architectural function, and then cases within each functional category were arranged by climatic group. The case studies are explored in two sections (Fig. 3).

Operational Definitions of Technical Parameters

To ensure consistent analysis and classification of technical characteristics, operational definitions for the technical variables used in the comparison tables were adopted.

Façade Types

The term single façade refers to façade systems consisting of a single outer layer that acts as the building's main envelope without an intervening air gap. Double façade refers to systems consisting of two layers separated by an air gap that allows for improved airflow and enhances the façade's environmental performance.

Control Systems

Control systems were classified according to the mechanism of operation of movable façade elements as follows:

- Manual Control relies on direct user intervention in operating façade elements, such as opening or closing movable parts.
- Manual Control — Rods and Pulleys System — relies on manual operation supported by a simple mechanical mechanism consisting of rods or pulleys to facilitate and control the movement of façade elements.
- Automatic Control (Automatic Device / Automated System) relies on mechanical or electronic systems that respond automatically to

environmental variables or predefined programs, without requiring direct user intervention.

These definitions were adopted to ensure standardised classification of operational and technical characteristics across all case studies under comparison.

Global Experiences

To illustrate the global prevalence of breathable façades and the diversity of their applications, global models from various regions were collected and analysed (Table 2). This analysis facilitates understanding of the differences and similarities between civilisations and the adaptation of environmental solutions to local conditions.

Regional Experiences

Regional models aim to demonstrate how traditional and modern principles of breathing façades can be adapted to local conditions. Table 3 presents these regional models with their basic analytical and comparative elements, facilitating understanding of their environmental and architectural characteristics.

Global Experiences: Selected Cases

This section focuses on analysing global models to explore the role of location, climate, climate adaptation, material selection, façade types, and building function in enhancing the effectiveness and resilience of breathing façades.

Site and Climate Analysis

The global distribution of models shows that most cases are concentrated in Southeast Asian countries, led by Vietnam, which alone accounts for 16 architectural models. This reflects the close connection between humid tropical climates and the need to develop breathable façades that respond to high temperatures, rainfall intensity, and humidity. Several models also appeared in India and Brazil, with four in each country — two nations with similar hot / humid tropical climates — reinforcing the idea that breathable façades were a direct response to challenging environmental conditions, aiming to achieve thermal comfort and provide natural ventilation (Table 4).

Conversely, individual cases in countries such as Canada, Germany, and Spain indicate that this

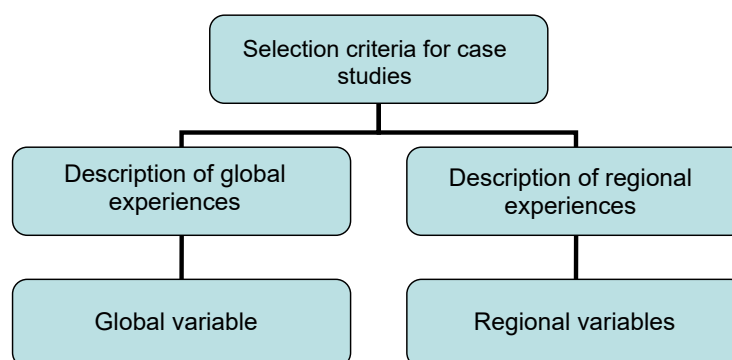


Fig. 3. Selection criteria for case studies

Table 2. Characteristics of Global Experiences (Part 1)

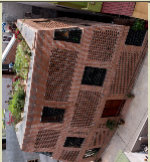
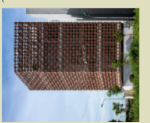
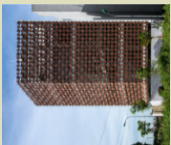
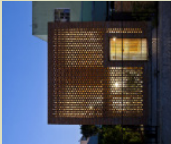
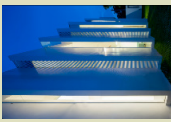
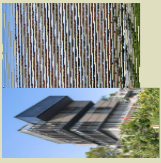
General Information		Key Elements of Breathing Façades				
Name	Picture	Location	Façade Type	Material	Control Mechanism	Function
Casa Nhà Bè		Vietnam	Double Static	Concrete – Glass	NA	Residential
Cueva de Ladrillos		Vietnam	Double Static	Brick	NA	
Cuckoo House		Vietnam	Double Static	Brick – Glass	NA	
Proper Breathing House		Vietnam	Double Static	Ceramic – Glass	NA	
NDC House		Vietnam	Double Static	Brick – Glass	NA	
Termitary House		Vietnam	Double Static	Brick – Glass	NA	
T House		Vietnam	Double Static	Brick – Glass	NA	
Tropical Cave		Vietnam	Double Kinetic	Wood – Glass	Manual control – system of robs and pulleys	
Tile Nest House		Vietnam	Double Static	Clay – Glass	NA	
The Light-house		Vietnam	Double Kinetic	Concrete – Glass	Manual control	

Table 2. Characteristics of Global Experiences (Part 2)

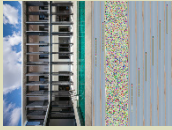
Name	Picture	Location	Façade Type	Material	Control Mechanism	Function
General Information			Key Elements of Breathing Façades			
Wall House		Vietnam	Single	Brick – Glass	NA	Residential
Brick Screen House		India	Double	Brick – Glass	NA	
HIVE House		India	Double	Metal – Glass	Automatic device – Automated system	
House of Shadow		Brazil	Single	Wood	Manual control	
MP Residence		Brazil	Double	Ceramic – Glass	NA	
The Manga		Brazil	Double	Metal – Glass	NA	
House BT		Thailand	Double	Steel – Glass	Manual control	
YPY 1731 Housing		Argentina	Double	Brick	NA	
'ARQ RIFA G'2010' House		Uruguay	Double	Brick – Glass	NA	
Stonewood House		Australia	Double	Stonewood – Glass	NA	

Table 2. Characteristics of Global Experiences (Part 3)

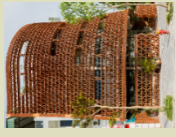
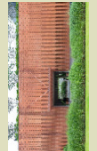
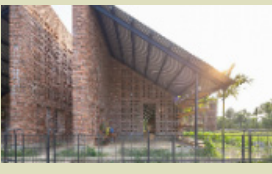
General Information		Key Elements of Breathing Façades				
Name	Picture	Location	Façade Type	Material	Control Mechanism	Function
Breathing Houses		Taiwan	Double Static	Metal – Glass	NA	Residential
Claudio Coello 121 Residential Building		Spain	Double Kinetic	Wood – Glass	Manual control	
Notre-Dame		Canada	Single Static	Brick	NA	
Premier Office		Vietnam	Double Static	Brick	NA	Office Buildings
Tropical Shed		Brazil	Single Static	Brick – Glass	NA	
Won & Won 63.5		South Korea	Double Static	Brick – Glass	NA	
Espacio Ngòi		Vietnam	Double Static	Clay – Glass	NA	Educational
Wyndham Clubhouse		Vietnam	Single Static	Brick	NA	
Sharana Daycare Center		India	Double Static	Terracotta – Glass	NA	Hospitality
Aalen University Extension		Germany	Double Kinetic	Wood – Glass	Manual control	Cafe

Table 2. Characteristics of Global Experiences (Part 4)

General Information	Name	Terra Cotta Studio	Terra Cotta Workshop	M. A. C. Community Center
	Picture			
	Location	Vietnam	Vietnam	India
Key Elements of Breathing façades	Façade Type	Single	Single	Single
		Static	Static	Static
	Material	Brick	Brick	Concrete
	Control Mechanism	NA	NA	NA
	Function	Workshop	Factory	Community

Note: NA (Not Applicable) indicates that the control mechanism is a feature associated exclusively with kinetic façades and therefore does not apply to static façades.

architectural approach has also spread to regions with temperate or cold climates, often through contemporary techniques or reinterpretations of the traditional concept. Based on the numerical distribution, tropical / monsoon climates are most strongly associated with the spread of these models, followed by hot tropical climates in India and Brazil, while cases in temperate or cold regions remain relatively fewer. Nevertheless, these examples are important for demonstrating the universality of the concept and the diversity of its applications.

Climate Adaptation

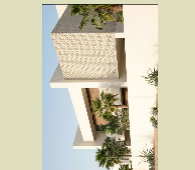
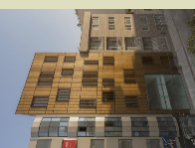
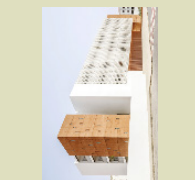
The analysis of the geographic and climatic distribution of the case studies reveals that breathable façades originally emerged in hot and humid climates, particularly in Southeast Asia and Latin America, where natural ventilation and heat-load reduction are critical concerns. This reflects a local adaptation, in which the architectural solution was directly driven by specific climatic conditions. However, the presence of similar models in Germany, Canada, and Spain demonstrates that the concept has not remained confined to its original context.

Instead, it has been reinterpreted and applied globally across diverse climatic environments. Consequently, breathable façades have evolved from a traditional local solution into a global architectural model capable of responding to a wide range of climatic and cultural conditions.

Building Materials

The analysis of global models reveals that brick was the most commonly used material, particularly in Vietnam, where it appeared in more than half of the cases, alongside clay and ceramics. This reflects the local availability of clay-based materials and their effectiveness in promoting ventilation and mitigating heat gain. Glass also featured prominently as a façade component, often used in combination with traditional materials. In contrast, India and Brazil employed a wider variety of materials, including metal, concrete, and terracotta, indicating a tendency to blend modern industrial products with conventional ones. European models (Spain and Germany) predominantly utilised wood and glass, aligning with regional sustainability priorities. In Canada, brick again emerged as the primary

Table 3. Characteristics of Regional Experiences

General Information		Key Elements of Breathing Façades				
Name	Picture	Location	Façade Type	Material	Control Mechanism	Function
Saadat Abad Residential Building		Iran	Double	Brick – Glass	NA	Residential
Ozgol Apartment		Iran	Single	Brick – Glass	Manual control	
Lima Villa		United Arab Emirates	Double	Concrete – Glass	NA	
Lantern House		Algeria	Double	Cement – Glass	NA	
Kohan Ceram Building		Iran	Double	Brick – Glass	Manual control	Office Buildings
Sharif Office Building		Iran	Double	Brick – Glass	Manual control	
Saadat Abad Commercial Office Building		Iran	Double	Wood – Glass	Manual control	
Concrete Phrontistery		Morocco	Double	Concrete – Glass	NA	
Cobogo House		Kuwait	Double	Tile – Glass	NA	Hospitality

Note: NA (Not Applicable) indicates that the control mechanism is a feature associated exclusively with kinetic façades and therefore does not apply to static façades.

Table 4. Distribution of locations and climates

Country	Number of Locations	Continent	Climate
Vietnam	16	Asia	Tropical Monsoon
India	4		Tropical Monsoon/ Subtropical
Brazil	4	South America	Tropical / Humid Subtropical
Argentina	1		Temperate
Uruguay	1		Temperate Oceanic
Australia	1	Oceania	Tropical / Arid
Thailand	1	Asia	Tropical Monsoon
South Korea	1		Temperate Continental
Taiwan	1		Subtropical / Tropical
Spain	1	Europe	Mediterranean
Germany	1		Temperate Oceanic
Canada	1	North america	Cold continental/ Subarctic

material, while Australia presented the only example of a stone-and-wood combination (Table 5). Overall, this diversity underscores the significant influence of both local resource availability and climatic conditions on material selection, alongside the growing impact of sustainability trends in contemporary architecture.

Façade Types

The analysis of façade types across the case studies reveals their role in simultaneously providing effective natural ventilation within buildings. Three main categories were identified:

- **Double-Skin Façades:** These were the most common type, particularly in Vietnam, where 10 out of 16 sites employed this system. Double-skin façades allow complete air circulation through a cavity between two layers: the inner layer can be opened or closed as needed, while the outer layer provides thermal protection against heat or cold. This system promotes natural airflow and enhances indoor environmental quality.

- **Single-Skin Façades:** These traditional façades feature limited openings and provide effective isolation from external climatic conditions. However, they are less effective than double-skin façades in regulating airflow and achieving natural ventilation.

- **Kinetic Façades:** These systems can be adjusted manually or automatically to modulate the intake of fresh air. While they offer flexibility, they may also increase the infiltration of outdoor pollutants if

not properly filtered, which can negatively impact indoor air quality.

Overall, double-skin façades were the most prevalent across the studied models, indicating a growing trend toward adaptable and environmentally responsive design strategies in diverse climatic regions (Table 6).

Building Types

The analysis of the case studies reveals that the majority of buildings were designated for residential use, alongside a range of other functions. In Vietnam, residential buildings dominated the 16 sites, with additional examples of office buildings, hospitals, cafes, workshops, and factories. This diversity reflects the broad applicability of breathable façades across various functional requirements. In India, most projects were residential, complemented by community and educational buildings. Similarly, Brazil's case studies consisted primarily of residential buildings, with some office buildings also present. In Argentina, Uruguay, Australia, Thailand, Taiwan, Spain, and Canada, residential buildings again constituted the majority. By contrast, South Korea focused exclusively on office buildings, while Germany's sole case study was an educational facility (Table 7).

Regional Experiences: Selected Cases

The regional models aim to demonstrate how traditional and modern principles of breathable

Table 5. Building Materials Used

Country	Material	Number of Buildings Used
Vietnam	Clay – Glass	2
	Brick	5
	Brick – Glass	5
	Ceramic – Glass	1
	Concrete – Glass	2
	Wood – Glass	1
India	Brick – Glass	1
	Terracotta – Glass	1
	Concrete	1
	Metal – Glass	1
Brazil	Brick – Glass	1
	Ceramic – Glass	1
	Wood	1
	Metal – Glass	1
Argentina	Brick	1
Uruguay	Brick – Glass	1
Australia	Stone – Wood – Glass	1
Thailand	Steel – Glass	1
South Korea	Brick – Glass	1
Taiwan	Metal – Glass	1
Spain	Wood – Glass	1
Germany	Wood – Glass	1
Canada	Brick	1

Table 6. Façade Types

Country	Façade Type				Control
	Double Façade	Single Façade	Static Façade	Kinetic Façade	
Vietnam	10		10		NA
	2			2	Manual control
		4	4		NA
India	1			1	Automatic device – Automated system
	2		2		NA
		1	1		NA
Brazi		1		1	Manual control
	2		2		NA
		1	1		NA
Argentina	1		1		NA
Uruguay	1		1		NA
Australia	1		1		NA
Thailand	1		1		Manual control
South Korea	1		1		NA
Taiwan	1		1		NA
Spain	1			1	Manual control
Germany	1			1	Manual control
Canada		1	1		NA

façades can be adapted to local conditions and available materials.

Site and Climate Analysis

The regional case studies were distributed across five countries: Iran (5 models), the United Arab Emirates, Kuwait, Algeria, and Morocco (one each). Iran accounted for the largest proportion of the studied models, reflecting the richness of its architectural heritage and the diversity of its climatic conditions — ranging from semi-arid climates in most areas to cold mountainous regions, which demand

distinct façade strategies. In the Arabian Gulf (the UAE and Kuwait), the models originated from hot, dry desert environments, highlighting the role of breathable façades in providing natural ventilation and shading. In contrast, the North African models (Algeria and Morocco) demonstrated adaptation to the Mediterranean climate, characterised by moderate coastal conditions and hot, dry interiors. In these cases, perforated façades were used to facilitate natural ventilation while simultaneously maintaining a decorative architectural character. Overall, semi-arid and hot, dry climates were the most prevalent among the regional models (Table 8).

Climate Adaptation

The regional case studies reveal how architecture in the Middle East and North Africa employs breathable façades as environmentally responsive solutions across diverse climatic contexts. In Iran, where the climate ranges from semi-arid to cold in mountainous areas, buildings incorporated façades that allow

Table 7. Distribution of Building Uses

Country	Residential	Office Buildings	Educational	Hospitality	Café	Workshop	Factory	Community
Vietnam	11	1	–	1	1	1	1	–
India	2	–	1	–	–	–	–	1
Brazil	3	1	–	–	–	–	–	–
Argentina	1	–	–	–	–	–	–	–
Uruguay	1	–	–	–	–	–	–	–
Australia	1	–	–	–	–	–	–	–
Thailand	1	–	–	–	–	–	–	–
South Korea	–	1	–	–	–	–	–	–
Taiwan	1	–	–	–	–	–	–	–
Spain	1	–	–	–	–	–	–	–
Germany	–	–	1	–	–	–	–	–
Canada	1	–	–	–	–	–	–	–

Table 8. Distribution of Locations and Climates

Country	Number of Locations	Continent	Climate
Iran	5	Asia	Hot and Dry Desert
United Arab Emirates	1		
Kuwait	1		
Algeria	1	Africa	Mediterranean Climate
Morocco	1		

summer ventilation while minimising winter heat loss, reflecting a dual adaptation to seasonal weather variations. In the Gulf countries (the UAE and Kuwait), characterised by hot, arid conditions, breathable façades prioritised the reduction of direct solar radiation while maintaining airflow, thereby improving thermal comfort despite extreme environmental conditions. Conversely, the North African models (Algeria and Morocco) offered solutions tailored to the mild Mediterranean climate along the coast and the drier conditions of the interior. Overall, these regional models exhibit a high degree of flexibility in adapting to diverse climatic patterns — ranging from hot and arid to semi-arid and temperate environments.

Building Materials

The analysis of materials used in the regional models reveals a clear preference for combining traditional and modern materials to suit local climatic conditions and functional requirements. In Iran, brick and glass dominate, reflecting the use of locally available materials. Wood combined with glass also appears in one Iranian site, indicating its application in smaller, more ventilated buildings. In the UAE and Morocco, concrete paired with glass reflects a modern, urban aesthetic well-suited to hot, arid climates. Glass facilitates the introduction of natural light while enabling controlled natural ventilation. Kuwait employs tiles combined with glass (Table 9), offering durability and reflective properties that help reduce heat gain. Algeria, meanwhile, uses cement with glass, likely for its thermal mass and structural resilience in the local climate.

Table 9. Building Materials Used

Country	Material	Number of Buildings Used
Iran	Brick – Glass	4
	Wood – Glass	1
United Arab Emirates	Concrete – Glass	1
Kuwait	Tile – Glass	1
Algeria	Cement – Glass	1
Morocco	Concrete – Glass	1

Façade Types

The analysis of façade types in the regional models reveals relatively limited diversity. Most buildings employ either double-skin or single-skin façades, with manual control systems implemented in certain cases. Double-skin façades facilitate natural ventilation and enhance indoor air quality, while the outer layer is typically constructed from materials that provide additional protection against harsh climatic conditions, such as extreme heat or strong winds. Iran exhibits a varied distribution of both double and single façades, with some models incorporating manual controls to regulate airflow as needed. In the UAE and Morocco, buildings utilise both façade types, though control mechanisms are simplified, as most structures do not require frequent adjustment. Kuwait and Algeria, however, rely primarily on manually controlled façades to enable ventilation in response to fluctuating climatic conditions (Table 10).

Building Types

The regional models reveal that residential and administrative buildings (offices) are the most common uses, reflecting the prevailing nature of urban activities in the region. Iran, for example, exhibits a mix of residential and administrative buildings, indicating the diversity of functional needs within its urban context (Table 11). This predominance of housing and administrative functions underscores the basic requirements of regional communities, while specialised uses — such as educational or hospitality facilities — remain limited in number and diversity.

Comparative Analysis of Global and Regional Models

The comparative analysis examines the similarities and differences between global and regional models across several key parameters. The evaluation begins with climate, location, and adaptation — identified as primary factors that shaped design responses — followed by an assessment of materials, façade patterns, and finally, building uses (Table 12).

As summarised in Table 12, global and regional models differ significantly across all analysed parameters:

Table 10. Façade Types

Country	Façade Type				Control
	Double Façade	Single Façade	Static Façade	Kinetic Façade	
Iran	1		1		NA
		1		1	Manual control
	3			3	Manual control
United Arab Emirates	1		1		NA
Kuwait	1		1		Manual control
Algeria	1		1		Manual control
Morocco	1		1		NA

Table 11. **Distribution of Building Uses**

Country	Residential	Office Buildings	Educational	Hospitality
Iran	2	3	–	–
United Arab Emirates	1	–	–	–
Kuwait	–	–	–	1
Algeria	1	–	–	–
Morocco	–	–	1	–

Table 12. **Comparative analysis between global and regional models**

Axis	Global Models	Regional Models
Location and Climate	Wide climatic diversity, dominated by humid tropical climates, with limited presence of temperate and hot, humid climates	Concentrated in hot, dry desert climates
Adaptation Strategies	Focused on combating high humidity	Focused on reducing heat gain in hot, dry conditions
Building Materials	Wide variety of materials (brick, concrete, wood, metal, glass)	Limited set of materials (brick, concrete, cement, and tile with glass)
Façade Systems	More diverse and flexible double-skin façades, combining movable glass with external protective layers, with manual and, in some cases, automatic controls	Simpler single or double-skin façades, with manual controls only
Building Uses	Predominantly residential, with diverse secondary uses including office buildings, educational facilities, and service activities (hospitals, cafes, factories)	Concentrated in residential and office buildings

- Location and climate reflect the different environmental challenges of controlling humidity in global contexts and confronting heat and solar radiation in regional ones.

- Adaptation strategies. In global models, adaptation focused on combating high humidity by promoting continuous natural ventilation to renew air and reduce indoor pollutants. In regional models, where the climate is hot and dry, the focus was on reducing heat gain and protecting interior spaces from direct solar radiation, while regulating ventilation to provide cooling without introducing hot or dusty air.

- Building Materials. This reflects a local trend toward simpler, more environmentally and resource-efficient solutions, compared to the greater flexibility observed in global models. This is also linked to the aesthetic and material expression of buildings, where locally available materials such as brick and wood are more sustainable than high-energy materials such as concrete and glass (Hammond and Jones, 2011; Dixit et al., 2010).

- Façade Systems. Global models relied on double-skin façades to enhance natural ventilation and improve indoor air quality (de Araújo and Bistafa, 2012; Stabile et al., 2017). Regional models, in contrast, reflected more practical but less flexible

solutions compared to their global counterparts (Gupta et al., 2022).

- Building Uses. Global models showed greater diversity in use patterns, while regional models tended to focus on primary uses — predominantly residential and administrative — with limited presence of other activities.

Conclusion

This study demonstrated that breathing façades — encompassing traditional architectural elements such as mashrabiya, jali screens, lattice screens, and cobogó — provide continuous natural ventilation. The results of the comparative analysis revealed that double-skin façades enhance ventilation by increasing the renewal of fresh air within buildings. This mechanism reduces pollutant accumulation in interior spaces and improves indoor air quality (IAQ). Furthermore, the use of locally sourced materials was found to contribute to a significant reduction in embodied energy. The findings also indicate that integrating double-skin façades with adaptive façade systems — which modulate openings to regulate ventilation as required — can improve both thermal performance and indoor comfort in hot-climate building designs. Collectively, these outcomes offer a viable framework that can be leveraged in the design of future buildings under similar climatic conditions.

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ДЫШАЩИЕ ФАСАДЫ КАК СТРАТЕГИИ РЕАГИРОВАНИЯ НА КЛИМАТИЧЕСКИЕ УСЛОВИЯ: ПРИМЕРЫ ИЗ РАЗЛИЧНЫХ КЛИМАТИЧЕСКИХ КОНТЕКСТОВ

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Аннотация

Введение. В данном исследовании оценивается эффективность дышащих фасадов как инновационного архитектурного решения, способствующего обеспечению непрерывной вентиляции, улучшению качества воздуха в помещении, снижению накопления загрязняющих веществ и уменьшению энергопотребления в различных климатических и географических условиях. **Цель исследования** — изучить использование этих фасадов в различных условиях и определить их гибкость и эффективность. **Методы.** Был применен описательный и сравнительный аналитический подход, в рамках которого были изучены 42 глобальные и региональные модели, охватывающие различные континенты и климатические условия. Модели были классифицированы по четырем основным критериям: географическое положение, строительные материалы, системы проектирования и схемы вентиляции, при этом для иллюстрации наиболее распространенных схем использовались таблицы. **Результаты** показывают, что глобальные модели делают акцент на разнообразных решениях, улучшающих вентиляцию и качество воздуха, в то время как региональные модели отличаются использованием недорогих, экологически устойчивых материалов, демонстрируя гибкость и эффективность. Эти результаты подтверждают экологическую и функциональную эффективность воздухопроницаемых фасадов в различных климатических условиях.

Ключевые слова: воздухопроницаемые фасады, естественная вентиляция, климатическая адаптация, качество воздуха в помещении, сравнительный анализ, устойчивая архитектура.

ACOUSTIC EVALUATION OF MOSQUES WITH TWO LOUDSPEAKERS: INFLUENCE OF GEOMETRY, SIZE, CEILING MATERIALS, LOUDSPEAKER POSITION, AND OCCUPANCY

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Abstract

Introduction. This study presents a comprehensive investigation of the acoustic characteristics of mosques equipped with two loudspeakers under varying conditions. It addresses the widespread challenge of poor acoustics in Indonesian mosques, which often results from architectural features, material choices, and suboptimal sound system design. **Methods.** Using acoustic simulation, the research systematically varied several parameters: geometry, prayer area size (ranging from 100 m² to 625 m²), ceiling material (acoustic tile ceiling vs. gypsum tile ceiling), loudspeaker position, and occupancy level (unoccupied vs. fully occupied). The primary focus is the optimisation of the Speech Transmission Index (STI) for speech intelligibility and Sound Pressure Level (SPL) uniformity. **Results.** The key findings indicate that loudspeaker placement (corner vs. center-front) does not significantly affect either STI or uniformity. However, in larger hall volumes (e.g., 3,516 m³ and 6,086 m³), minor differences in sound uniformity (SPL Max–Min) were observed depending on loudspeaker position. In contrast, room volume, ceiling material, and occupancy significantly influence STI; larger volumes and lower absorption are associated with reduced clarity. Sound uniformity is also negatively affected by increased room volume and reflective, complex ceiling shapes (e.g., pyramidal), whereas increased absorption can heighten the dominance of the direct sound field, potentially diminishing uniformity. **Conclusions.** The study establishes that to achieve an STI > 0.5 and SPL variation < 6 dB across all occupancy conditions, the mosque volume should not exceed 1,125 m³. Furthermore, to ensure adequate speech intelligibility (STI > 0.5) in the unoccupied (worst-case) condition, the maximum reverberation time (RT) at 1 kHz should be limited to 2.5 seconds. These findings provide practical, evidence-based guidelines for the acoustic design of small- to medium-sized Indonesian mosques.

Keywords: mosque, room acoustics, loudspeakers, simulation, sound uniformity, speech transmission index.

Introduction

The acoustical performance of mosques, as significant religious and architectural structures, profoundly impacts the spiritual experience of congregants during various rituals, including prayer, sermons, and Quran recitation (Sert and Karaman, 2021; Kaygısız, Semerci and Sayın, 2024). This necessitates a comprehensive understanding of how architectural features, material properties, and sound system design interact to shape the aural environment within these unique spaces (Sert and Karaman, 2021; Handryant, 2021). The intricate interplay of these factors is especially critical in mosques, where auditory clarity is paramount for the comprehension of religious texts and sermons, thereby enhancing the spiritual engagement of worshippers (Aydın, Kocyigit and Dalkılıç, 2021).

In Indonesia, the mosque has historically been the most significant structure in Islamic civilisation. As the most populous Muslim country, Indonesia is home to over three hundred thousand mosques (Sistem Informasi Masjid, 2025). Given this vast number, ensuring optimal acoustic conditions for speech intelligibility and overall sound quality within these structures presents a significant challenge,

particularly considering their diverse architectural styles and construction materials (Adnan et al., 2018; Sert and Karaman, 2021). The study conducted by Sudarsono et al. (2019) shows that acoustic problems are still prevalent in Indonesian mosques. Several factors contribute to this issue, including the lack of prior acoustic considerations during the design phase, the use of inappropriate building materials, and suboptimal loudspeaker placement within worship halls (Prawirasasra and Mubarak, 2017). Moreover, a common misconception persists in Indonesia that good acoustic design can be achieved solely by installing a high-quality sound system, without due consideration of the room's inherent acoustic properties (Sudarsono et al., 2019). This situation is further exacerbated by the tendency of many mosque committees to prioritise aesthetic appeal or budget constraints over expert acoustic planning (Latifah et al., 2023; Handryant, 2021). These challenges underscore the urgent need for simplified, evidence-based guidance to facilitate effective acoustic design without requiring comprehensive specialised expertise.

Sound reinforcement systems have become an integral component of room acoustic design,

particularly in modern mosques. However, most studies on mosque acoustics have predominantly focused on architectural parameters and material properties, often neglecting the comprehensive impact of loudspeaker systems on overall acoustic comfort and speech intelligibility (Abdou, 2003; Othman et al., 2016; Pratiwi et al., 2023; Kaygısız, Semerci and Sayın, 2024). Therefore, an integrated strategy that addresses both the inherent architectural acoustics of mosques and the design of sound reinforcement systems is essential for improving speech intelligibility and achieving uniform sound distribution.

One of the challenges in the acoustic design of mosques in Indonesia is the dynamic nature of occupancy, which significantly affects acoustic conditions. In general, two main occupancy states can be distinguished: Jumah prayer and normal congregational prayer. Jumah prayer is characterised by a significantly higher occupancy rate, which increases sound absorption, resulting in good speech intelligibility but often poor sound uniformity. In contrast, normal congregational prayer typically has a lower occupancy, leading to decreased sound absorption and potentially longer reverberation times that can compromise clarity (Latifah et al., 2023). This dynamic shift in occupancy underscores the need for a robust acoustic design that can maintain optimal speech intelligibility and sound uniformity across varying absorption levels.

Several studies have investigated the acoustic quality of mosques through field measurements (Kitapci and Çelik Başok, 2021; Masih et al., 2021; Arinta et al., 2022; Syazana et al., 2023). These studies provide valuable information about existing conditions and enable comparisons with established standards. However, such measurements are typically conducted in unoccupied mosques, which may not accurately reflect the acoustic experience during congregational prayers, when occupancy significantly alters sound absorption characteristics. Furthermore, field measurements cannot be used to evaluate the effect of parameter variations on acoustic conditions. This highlights the need for advanced acoustic modeling techniques capable of simulating diverse scenarios, including varying occupancy levels and material configurations (Pratiwi et al., 2023; Sudarsono et al., 2023).

The aim of this study is to comprehensively investigate the acoustic characteristics of mosques under varying occupancy levels, with a specific focus on optimising speech intelligibility and sound uniformity through strategic loudspeaker placement and material selection using acoustic simulation. The study focuses on mosques equipped with two loudspeakers, owing to their widespread adoption in smaller to medium-sized prayer halls. The findings of this study are expected to provide practical,

evidence-based guidelines for the acoustic design of Indonesian mosques, ensuring enhanced speech intelligibility and uniform sound distribution across diverse occupancy scenarios and architectural configurations.

Method

This study evaluates the acoustic conditions inside a mosque by systematically varying several parameters, including mosque geometry, size, application of acoustic materials, loudspeaker positions, and occupancy levels, as detailed in Table 1. Acoustic simulation employing loudspeakers as sound sources was used to assess acoustic performance, with a particular focus on speech intelligibility and sound uniformity. The simulations were conducted using Fohhn Designer, a web-based simulation tool capable of modeling acoustic conditions with loudspeakers as sound sources (Fohhn Designer, 2025). This approach enables a systematic analysis of how each variable contributes to overall acoustic quality, thereby facilitating the development of evidence-based design recommendations for various mosque typologies.

The prayer area size was varied between 100 m² and 625 m² to represent the typical range of community mosque sizes, which are predominant in Indonesia (Sistem Informasi Masjid, 2025). The prayer area was modelled with a rectangular shape, as this geometric configuration is frequently encountered in existing mosque designs. The rectangular plan is highly efficient for organising worshippers into neat, straight rows, all facing the Qibla (the direction of the Kaaba in Mecca) (Lukman et al., 2023; Ali and Mustafa, 2023). Furthermore, a study on Javanese mosques found that the majority of mosque plans were typically square (Budi, 2006).

The ceiling shape was varied between flat and pyramidal configurations. The flat ceiling was chosen to represent a common prayer room design, while

Table 1. Variable evaluated in the study

Variables	Variation	Remarks
Prayer area size	10 m x 10 m 15 m x 15 m 20 m x 20 m 25 m x 25 m	Wall height: 5 m
Ceiling shape	Flat Pyramid Shaped	Pyramidal ceiling angle: 40°
Ceiling material	Gypsum Acoustic tile	
Occupancy	Fully occupied Unoccupied	Occupancy was simulated by modifying the absorption coefficients of the floor surface
Loudspeaker position	Front walls Front corners	Loudspeaker height: 3 m

the pyramidal ceiling was selected to reflect the typical roof forms of traditional Indonesian mosques, particularly in Java (Fikriyati, 2023). In the simulation, the ceiling angle was set to 40° , and the pyramidal ceiling dimensions were scaled proportionally to the prayer area. Visualisations of the ceiling shapes are presented in Fig. 1. The wall height was fixed at 5 m across all models.

Room volume is one of the critical factors influencing reverberation time and speech intelligibility, necessitating careful consideration in mosque design (Latifah et al., 2023). In this study, the room volume was calculated based on the variations in ceiling shape and prayer area size, yielding values ranging from 500 m^3 to $6,086 \text{ m}^3$.

The materials used in the mosque models were selected to represent typical construction practices. Walls were defined as painted concrete. Two ceiling types were examined: a hard, reflective ceiling representing standard construction (gypsum tile), and an acoustically absorptive ceiling (acoustic tile) to investigate the impact of sound-absorbing materials. Occupancy was also varied by modifying the sound absorption characteristics of the floor surface. The unoccupied condition was represented by carpet flooring, while the fully occupied condition was simulated by defining the floor as fully occupied by seated congregants, based on absorption coefficients reported by Oldham, Elkhateeb, and Science (2008). Detailed absorption coefficients for all materials used in this study are presented in Table 2. This approach effectively models the varying acoustic absorption characteristics between an unoccupied space and a fully populated prayer

hall, which is crucial for assessing dynamic acoustic performance.

This study incorporates two loudspeakers to investigate the effect of their placement on acoustic parameters within the mosque environment. As the simulation software (Fohhn Designer) only includes a database of Fohhn loudspeakers, the models were selected carefully to represent typical loudspeakers used in mosques. For this study, two 5-inch box loudspeakers (Fohhn Arc AT-05) were used in the simulations, as shown in Fig. 2. Each loudspeaker has a nominal coverage angle of 90° horizontally and 90° vertically, along with a frequency response tailored for speech applications, ensuring a realistic representation of sound reinforcement systems commonly found in mosques. The loudspeakers were positioned at a height of 3 m above the floor, aimed toward the rear wall. Two different placement configurations were simulated: at the front corners and at the center of the front wall, as illustrated in Fig. 3. This approach enables a comprehensive evaluation of how varying source locations interact with room acoustics and influence critical parameters, such as sound pressure level distribution and clarity, which are essential for effective speech communication in congregational settings.

This study focused on speech intelligibility and sound uniformity, which are essential parameters for khutbah (sermon) and congregational prayers (Sudarsono et al., 2019; Othman et al., 2016; Kitapci and Çelik Başok, 2021; Sarwono et al., 2020). Speech intelligibility was evaluated using the Speech Transmission Index (STI), a standardised method for the objective assessment of speech transmission

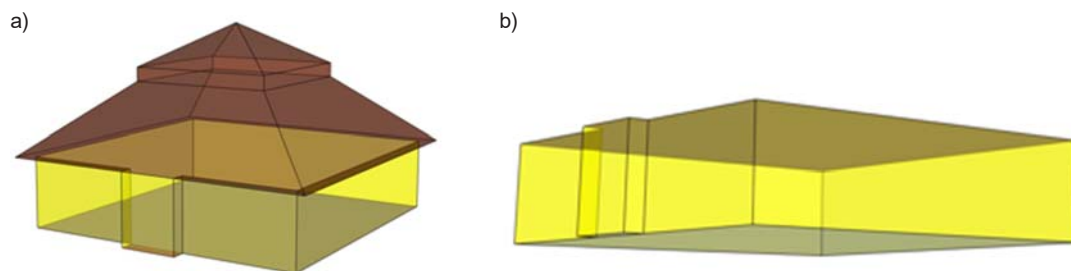


Fig. 1. Ceiling configurations simulated in this study: (a) pyramidal, (b) flat

Table 2. Sound absorption coefficients of materials used in the study

Type of Variations	Variations	Frequency						
		125	250	500	1000	2000	4000	8000
Walls	Painted concrete wall / floor (Fohhn Designer, 2025)	0.08	0.05	0.08	0.09	0.10	0.09	0.09
Ceiling	Generic, gypsum board, thickness of 0.625, 2 layers, 16-inch OC, 2x4 wood studs (Fohhn Designer, 2025)	0.28	0.12	0.10	0.08	0.14	0.09	0.06
	Acoustic ceiling (Fohhn Designer, 2025)	0.46	0.60	0.60	0.72	0.68	0.52	0.52
Floor	Carpet, commercial on concrete, floor (Fohhn Designer, 2025)	0.04	0.06	0.10	0.22	0.40	0.48	0.7
	The absorption coefficient of the fully occupied mosque (seated congregation) (Oldham et al., 2008)	0.19	0.19	0.75	0.89	0.86	0.97	0.99



Fig. 2. Fohhn Arc AT05 loudspeaker

quality (IEC 60268–16, 2003; Bjor, 2023; Jørgensen, 2014; Kobayashi and Kondo, 2019). The STI values used for analysis represent the spatial average across the prayer hall. Sound uniformity was assessed by calculating the difference between the maximum and minimum sound pressure levels (SPL) across the prayer area. In addition to these two parameters, reverberation time (RT) at 1 kHz was also examined, as optimal reverberation is crucial for both recitation and sermon / speech intelligibility in mosque environments (Elkhateeb and Eldakdoky, 2022).

The STI targets were selected with consideration of two occupancy scenarios: fully occupied and unoccupied. STI is closely related to the sound absorption within the mosque, with the worst-case condition typically occurring in the unoccupied scenario due to the absence of acoustic damping provided by the congregation. Accordingly, this study establishes a lower STI target for the unoccupied condition, acknowledging the practical challenges of achieving optimal intelligibility without the absorptive effect of worshippers. An STI target above 0.5 was selected for the unoccupied condition to ensure that intelligibility remains adequate even in the most demanding acoustic state, with further improvement expected under full occupancy (Farrasti, Sarwono, and Mangkuto, 2024). An STI of 0.5 is generally regarded as the minimum acceptable value for delivering complex messages with familiar context, and is commonly used as a design target for spaces

such as shopping malls and public offices (ANSI/ASA S3.5, 2017). This scenario-specific approach to STI targets ensures that the acoustic design is optimised for both peak congregational events and regular daily use, reflecting the diverse functional demands of a mosque.

To ensure good sound uniformity, the difference between the maximum and minimum sound pressure levels should ideally remain within a narrow range, typically less than 6 dB, to avoid significant variations in perceived loudness (Zohra, 2016). A difference of 6 dB is generally considered the maximum acceptable variation before a typical listener begins to consciously notice that the sound level differs significantly from one seat to another (American National Standards Institute, 2017).

Results

Effect of Parameter Variations on STI

The effect of parameter variations on the Speech Transmission Index (STI) was analysed using linear regression models, revealing quantitative relationships between architectural parameters, material properties, loudspeaker configurations, and the resulting speech intelligibility. The linear regression analysis indicated that STI values are significantly influenced by room volume, ceiling material, and occupancy, with a correlation coefficient of $R = 0.965$, as shown in Table 3. The results demonstrate that larger room volumes are associated with lower STI values. This relationship can be attributed to the proportional dependence of reverberation time on room volume; reverberation time is a critical determinant of speech intelligibility, as excessively long reverberation times cause overlapping of successive sounds, thereby diminishing clarity (Kunchur, 2019).

The STI is also influenced by ceiling material and occupancy, as both factors affect the sound absorption within the space. Specifically, materials with higher sound absorption coefficients — such as acoustic ceiling tiles or the presence of a congregation — effectively reduce reverberation time, leading to improved STI values (Galbrun and Kitapçı, 2014).

The use of acoustic tiles on the ceiling significantly enhances speech intelligibility, with

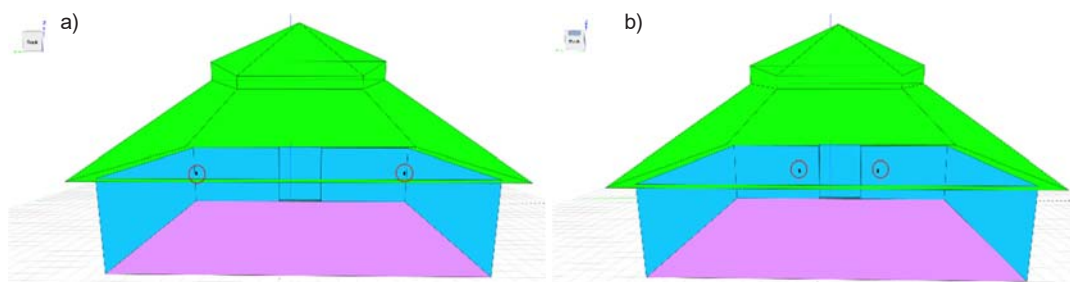


Fig. 3. Loudspeaker positions: (a) at the corner of the front wall, (b) at the centre of the front wall

Table 3. Multiple linear regression model for STI

Model Fit		
Model	R	R ²
1	0.965	0.932

Model Coefficients – STI

Predictor	Estimate	SE	t	p
Intercept ^a	0.537	0.00769	69.82	<.001
Room volume	-1.27e ⁻⁵	2.02e ⁻⁶	-6.31	<.001
Ceiling material:				
acoustic tile — gypsum	0.156	0.00699	22.34	<.001
Occupancy:				
fully occupied — unoccupied	0.118	0.00699	16.86	<.001

STI values exceeding 0.6, which indicates good speech intelligibility. This improvement was not observed in simulations with gypsum ceilings. These findings highlight the benefit of incorporating acoustic materials on ceilings, particularly given that most mosque designs typically feature hard-surface materials for walls and floors. The implementation of such materials can optimise acoustic conditions by reducing excessive reverberation, thereby improving speech clarity for sermons and recitations (Eldakdoky, 2016).

Effect of Parameter Variations on Sound Uniformity

The effect of parameter variations on sound uniformity was evaluated using a linear regression model. This analysis aimed to quantify how modifications to mosque geometry, acoustic material application, loudspeaker positioning, and occupancy levels influence the evenness of sound distribution throughout the prayer hall. The model indicated that sound distribution is significantly affected by room volume, occupancy, ceiling material, and ceiling shape, with a correlation coefficient of $R = 0.942$, as shown in Table 4. The sound from two loudspeakers can only be distributed effectively over a limited area, which reduces sound uniformity in larger rooms. The non-uniformity in sound distribution becomes more pronounced in larger volumes, where the inverse square law dictates more rapid attenuation of sound intensity with increasing distance from the source (Yang and Kang, 2021).

Sound uniformity is also significantly affected by ceiling shape. The results demonstrate that better sound uniformity is achieved with a flat ceiling. In contrast, complex ceiling geometries, such as pyramidal or vaulted structures, tend to produce uneven reflections, leading to significant variations in sound pressure levels across the space (Adnan et al., 2018).

Another factor affecting sound uniformity is the addition of absorptive surfaces, resulting from

Table 4. Multiple linear regression model for sound uniformity

Model Fit		
Model	R	R ²
1	0.942	0.887

Model Coefficients – SPL Max-Min

Predictor	Estimate	SE	t	p
Intercept	-0.788	0.284	-2.77	0.007
Occupancy:				
fully occupied — unoccupied	1.928	0.252	7.66	<.001
Ceiling material:				
acoustic tile — gypsum	2.757	0.252	10.96	<.001
Ceiling shape:				
pyramidal — flat	1.790	0.273	6.57	<.001
Room volume	9.23e ⁻⁴	7.86e ⁻⁵	11.74	<.001

full occupancy or the use of sound-absorbing materials on the ceiling. The introduction of sound-absorbing materials reduces the reflected sound field, making the direct sound more dominant and thereby contributing to uneven sound distribution (Setiyowati, 2012).

Acoustic Evaluation of Mosques in Unoccupied Condition

The unoccupied condition was evaluated to represent scenarios with a small number of worshippers. In this condition, sound uniformity was found to be adequate across all variations; therefore, the analysis focused primarily on the STI parameter. Ceiling type did not significantly affect STI values; rather, STI was predominantly influenced by room volume. This observation is consistent with prior research highlighting that larger volumes inherently increase reverberation time, thereby degrading speech intelligibility in unoccupied spaces (Abdullah and Zulkefli, 2014).

Fig. 4(a) presents the simulation results for mosques with an acoustic ceiling. The application of acoustic ceiling tiles improves STI across all room volumes, with values exceeding 0.5 in all cases. This improvement is attributed to reduced sound reflections from the ceiling, which increase the dominance of direct sound. The relationship between STI and room volume for mosques with acoustic ceilings is expressed in Equation (1):

$$STI = -9 \times 10^{-6} * Room\ volume + 0.7031 \quad (1)$$

Fig. 4(b) shows the simulation results for mosques without acoustic treatment (gypsum ceiling). In this configuration, STI is primarily influenced by room volume, with an R^2 of 0.84, indicating a strong relationship. The predictive model for STI in unoccupied mosques without absorptive ceiling materials is given in Equation (2):

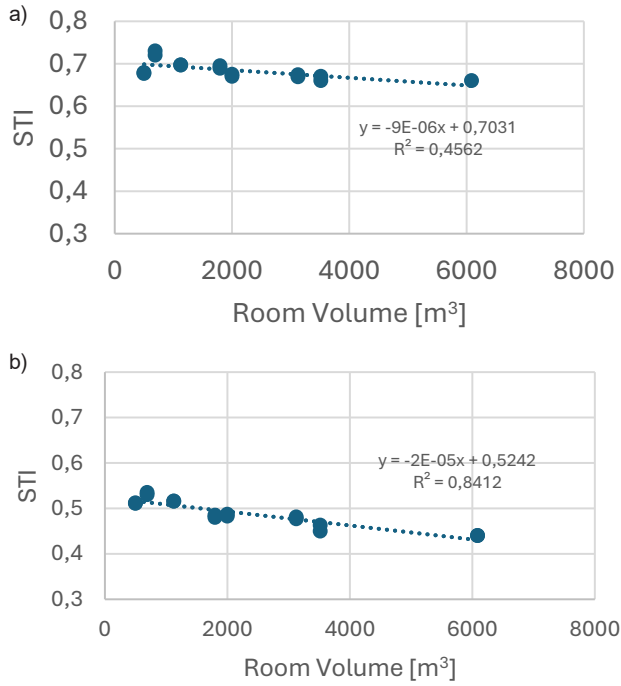


Fig. 4. Relationship between room volume and STI in unoccupied condition: (a) with acoustic tile ceiling, (b) with gypsum tile ceiling

$$STI = -2 \cdot 10^{-5} \cdot \text{Room volume} + 0.5242 \quad (2)$$

These results indicate that the use of acoustic tiles on the ceiling is generally effective in achieving good speech intelligibility, owing to reduced reflections from the ceiling surface. Under fully occupied conditions, STI values are expected to improve further due to the additional sound absorption provided by the congregation.

Acoustic Evaluation of Mosques in Fully Occupied Condition

The fully occupied condition was evaluated to represent the scenario of Jumah (Friday) prayer. In this condition, the analysis focused primarily on sound uniformity, as STI targets were already achieved across all variations in the unoccupied state. The main challenge was observed in sound uniformity, which varied significantly with room volume. This finding emphasises the critical need for more sophisticated acoustic design in larger mosques during periods of high occupancy, to ensure adequate sound coverage and clarity for all worshippers.

Fig. 5 illustrates the relationship between room volume and sound uniformity in the fully occupied condition. In general, sound uniformity deteriorates with increasing room volume. It should be noted that these results were obtained using only two loudspeakers; different outcomes may be expected with a greater number of loudspeakers.

The relationship between sound uniformity and room volume for fully occupied mosques is expressed in Equations (3) and (4). Equation (3) corresponds to

rooms with gypsum tile ceilings, while Equation (4) corresponds to rooms with acoustic tile ceilings:

$$\text{Sound Uniformity} = 0.001 \cdot \text{Room volume} + 1.9253 \quad (3)$$

$$\text{Sound Uniformity} = 0.0015 \cdot \text{Room volume} + 3.3211 \quad (4)$$

Sound uniformity is influenced by the reflective characteristics of the room. Greater reflection tends to distribute sound more evenly throughout the space. Consequently, as shown in Fig. 5(a), gypsum tile ceilings — which are more reflective — provide more uniform sound distribution compared to acoustic tile ceilings, as shown in Fig. 5(b). This suggests a trade-off: materials that enhance speech intelligibility by reducing reflections may simultaneously diminish sound uniformity in expansive spaces, particularly when only a limited number of loudspeakers are used (Din, Yong, and Razak, 2016).

Robust Design Recommendation for Mosques with Two Loudspeakers

This section synthesises the findings into design principles, offering practical guidance for architects on achieving optimal acoustic performance in mosque environments. Based on the results, a robust design recommendation is proposed that balances speech intelligibility with sound distribution.

The study systematically varied prayer hall areas from 100 m² to 625 m² with a standard wall height of 5 m, yielding volumes ranging from 500 m³ to 3,125 m³ for flat ceiling configurations. For more complex geometries, such as pyramidal ceilings, volumes reached up to 6,086 m³, as detailed in Table 5. Although a broad range was investigated,

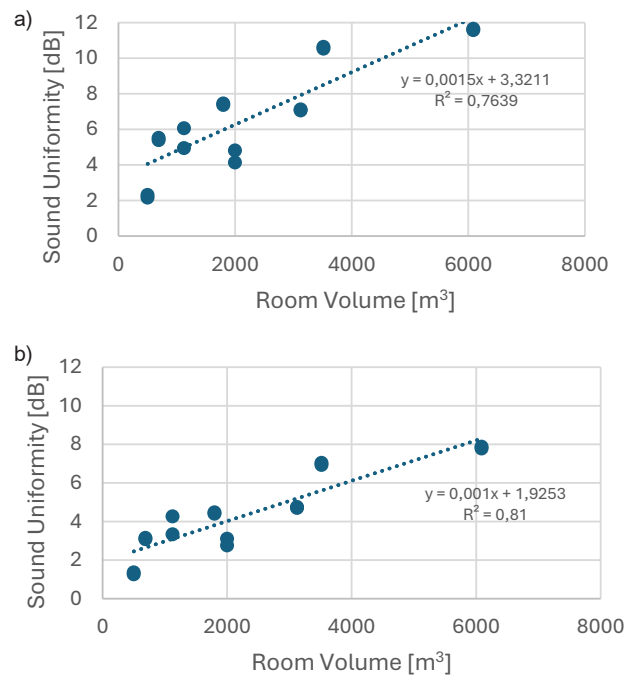


Fig. 5. Relationship between room volume and sound uniformity on fully occupied condition: (a) with acoustic tile ceiling (b) with gypsum tile ceiling

Table 5. STI and sound uniformity data from different variations. Grey shading indicates values that meet the design criteria

No.	Prayer area size [m ²]	Room volume [m ³]	Loudspeaker position	Ceiling shape	Ceiling material	Room occupancy	STI	SPLmax–SPLmin [dB]
1	100	500	Front wall	Flat	Gypsum	Fully occupied	0.663	1.26
2	100	500	Front corners	Flat	Gypsum	Fully occupied	0.662	1.36
3	100	500	Front wall	Flat	Gypsum	Unoccupied	0.512	0.48
4	100	500	Front corners	Flat	Gypsum	Unoccupied	0.511	0.52
5	100	500	Front wall	Flat	Acoustic tile	Fully occupied	0.757	2.15
6	100	500	Front corners	Flat	Acoustic tile	Fully occupied	0.756	2.3
7	100	500	Front wall	Flat	Acoustic tile	Unoccupied	0.679	1.36
8	100	500	Front corners	Flat	Acoustic tile	Unoccupied	0.677	1.46
9	100	689.5	Front wall	Pyramidal	Gypsum	Fully occupied	0.66	3.08
10	100	689.5	Front corners	Pyramidal	Gypsum	Fully occupied	0.66	3.15
11	100	689.5	Front wall	Pyramidal	Gypsum	Unoccupied	0.54	1.5
12	100	689.5	Front corners	Pyramidal	Gypsum	Unoccupied	0.53	1.54
13	100	689.5	Front wall	Pyramidal	Acoustic tile	Fully occupied	0.79	5.39
14	100	689.5	Front corners	Pyramidal	Acoustic tile	Fully occupied	0.78	5.51
15	100	689.5	Front wall	Pyramidal	Acoustic tile	Unoccupied	0.73	4.21
16	100	689.5	Front corners	Pyramidal	Acoustic tile	Unoccupied	0.72	4.31
17	225	1125	Front wall	Flat	Gypsum	Fully occupied	0.682	3.33
18	225	1125	Front corners	Flat	Gypsum	Fully occupied	0.694	4.26
19	225	1125	Front wall	Flat	Gypsum	Unoccupied	0.516	1.37
20	225	1125	Front corners	Flat	Gypsum	Unoccupied	0.516	1.55
21	225	1125	Front wall	Flat	Acoustic tile	Fully occupied	0.779	4.94
22	225	1125	Front wall	Flat	Acoustic tile	Unoccupied	0.697	3.45
23	225	1125	Front corners	Flat	Acoustic tile	Unoccupied	0.697	4.24
24	225	1125	Front corners	Flat	Acoustic tile	Fully occupied	0.778	6
25	225	1797.4	Front wall	Pyramidal	Gypsum	Fully occupied	0.69	4.47
26	225	1797.4	Front corners	Pyramidal	Gypsum	Fully occupied	0.61	4.4
27	225	1797.4	Front wall	Pyramidal	Acoustic tile	Unoccupied	0.7	5.96
28	225	1797.4	Front corners	Pyramidal	Acoustic tile	Unoccupied	0.69	5.88
29	400	2000	Front wall	Flat	Gypsum	Fully occupied	0.662	2.76
30	400	2000	Front corners	Flat	Gypsum	Fully occupied	0.656	3.1
31	400	2000	Front wall	Flat	Acoustic tile	Fully occupied	0.837	4.13
32	400	2000	Front corners	Flat	Acoustic tile	Fully occupied	0.757	4.8
33	400	2000	Front wall	Flat	Acoustic tile	Unoccupied	0.675	2.55
34	400	2000	Front corners	Flat	Acoustic tile	Unoccupied	0.67	2.96
35	625	3125	Front wall	Flat	Gypsum	Fully occupied	0.66	4.75
36	625	3125	Front corners	Flat	Gypsum	Fully occupied	0.656	4.7
37	625	3125	Front wall	Flat	Acoustic tile	Unoccupied	0.674	4.95
38	625	3125	Front corners	Flat	Acoustic tile	Unoccupied	0.669	4.9
39	225	1797.4	Front wall	Pyramidal	Gypsum	Unoccupied	0.49	2.21
40	225	1797.4	Front corners	Pyramidal	Gypsum	Unoccupied	0.48	2.17
41	225	1797.4	Front wall	Pyramidal	Acoustic tile	Fully occupied	0.76	7.45
42	225	1797.4	Front corners	Pyramidal	Acoustic tile	Fully occupied	0.75	7.36
43	400	2000	Front wall	Flat	Gypsum	Unoccupied	0.487	1.05
44	400	2000	Front corners	Flat	Gypsum	Unoccupied	0.483	1.06
45	625	3125	Front wall	Flat	Gypsum	Unoccupied	0.481	1.86
46	625	3125	Front corners	Flat	Gypsum	Unoccupied	0.477	1.83
47	625	3125	Front wall	Flat	Acoustic tile	Fully occupied	0.764	7.11
48	625	3125	Front corners	Flat	Acoustic tile	Fully occupied	0.759	7.05
49	400	3516.4	Front wall	Pyramidal	Gypsum	Fully occupied	0.6	7.04
50	400	3516.4	Front corners	Pyramidal	Gypsum	Fully occupied	0.59	6.93
51	400	3516.4	Front wall	Pyramidal	Gypsum	Unoccupied	0.46	3.88

Table 5 (Ending)

No.	Prayer area size [m ²]	Room volume [m ³]	Loudspeaker position	Ceiling shape	Ceiling material	Room occupancy	STI	SPLmax–SPLmin [dB]
52	400	3516.4	Front corners	Pyramidal	Gypsum	Unoccupied	0.45	3.81
53	400	3516.4	Front wall	Pyramidal	Acoustic tile	Fully occupied	0.74	10.63
54	400	3516.4	Front corners	Pyramidal	Acoustic tile	Fully occupied	0.74	10.53
55	400	3516.4	Front wall	Pyramidal	Acoustic tile	Unoccupied	0.67	8.89
56	400	3516.4	Front corners	Pyramidal	Acoustic tile	Unoccupied	0.66	8.79
57	625	6086.9	Front wall	Pyramidal	Gypsum	Fully occupied	0.58	7.87
58	625	6086.9	Front corners	Pyramidal	Gypsum	Fully occupied	0.58	7.78
59	625	6086.9	Front wall	Pyramidal	Gypsum	Unoccupied	0.44	4.43
60	625	6086.9	Front corners	Pyramidal	Gypsum	Unoccupied	0.44	4.35
61	625	6086.9	Front wall	Pyramidal	Acoustic tile	Fully occupied	0.73	11.65
62	625	6086.9	Front corners	Pyramidal	Acoustic tile	Fully occupied	0.72	11.57
63	625	6086.9	Front wall	Pyramidal	Acoustic tile	Unoccupied	0.66	9.84
64	625	6086.9	Front corners	Pyramidal	Acoustic tile	Unoccupied	0.65	9.74

the final “robust design” recommendation is based on a volume of 1,125 m³. This specific value serves as a critical acoustic threshold: below this volume, achieving an STI > 0.5 and SPL variation < 6 dB remains feasible across various occupancy levels. Beyond this threshold, acoustic degradation becomes substantially more difficult to mitigate with a standard two-loudspeaker configuration. This is exemplified by data points 39 and 40 in Table 5, which show that STI values fall below 0.5 in unoccupied conditions for rooms with a volume of 1,797.4 m³. These results suggest that for larger mosque volumes, a more sophisticated acoustical design approach — potentially involving distributed loudspeaker systems or advanced acoustic treatments — would be necessary to meet the robust criteria.

Statistical analysis and regression models (Tables 3 and 4) indicate that, for the general dataset, the choice between corner and center-front loudspeaker placement does not significantly affect STI or sound uniformity. However, in larger hall volumes (e.g., 3,516 m³ and 6,086 m³, as shown in Table 5), minor differences in sound field unevenness (SPL Max – Min) were observed depending on speaker position. Therefore, while the influence of loudspeaker placement is negligible in small to medium-sized rooms compared to room volume and ceiling material, its impact may become more noticeable in larger halls and warrants further investigation.

Speech intelligibility is typically evaluated in relation to the reverberation time, which is normally measured in unoccupied conditions and reflects the level of sound reflections within the mosque. According to the data, STI values are negatively correlated with reverberation time, indicating that longer reverberation times reduce speech clarity (Kaygısız, Semerci, and Sayın, 2024). This relationship was modeled using linear regression,

yielding a strong correlation coefficient of $R = 0.97$. Since an STI above 0.5 is desired in unoccupied conditions, the maximum permissible reverberation time can be derived from the simulation data. To achieve good speech intelligibility in unoccupied conditions, the recommended upper limit for reverberation time is 2.5 seconds, as shown in Fig. 6. This value aligns with recommendations from several previous studies, which typically suggest ranges of 1.6 to 1.8 seconds (Sudarsono et al., 2023; Ismail, 2013). Furthermore, the presence of worshippers during occupancy reduces reverberation time, thereby enhancing speech intelligibility. Congregants act as a substantial sound-absorbing mechanism, which can improve acoustic parameters such as clarity and the speech transmission index, both crucial for the functional performance of a mosque (Gül and Çalışkan, 2013).

Sound optimisation is particularly crucial for large mosques, largely due to their increased volume and surface areas, which necessitate more sophisticated acoustic treatments and sound

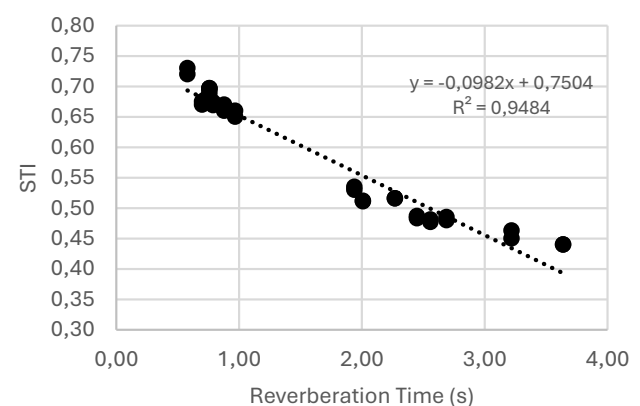


Fig. 6. Relationship between STI and reverberation time

reinforcement strategies to maintain desirable intelligibility and sound pressure levels across the entire prayer hall (Adnan et al., 2018). The use of absorptive materials is key to controlling sound reflections, thereby improving speech clarity and reducing excessive reverberation (Zohra, 2016). However, excessive use of absorptive materials can compromise sound uniformity and diminish the sense of a sacred space by substantially reducing natural reverberation. Therefore, a careful balance must be struck between reverberation control and maintaining sufficient sound reflection to preserve the mosque's architectural acoustics and spiritual ambiance (Elkhateeb and Eldakdoky, 2022). This optimal condition can be achieved by iterating through various design options using simulation during the design stage. Such simulations allow designers to predict key acoustic parameters, such as reverberation time and speech transmission index, under various occupancy and material conditions before physical construction, thus enabling proactive optimisation of the acoustic environment (Zohra, 2016; Benferhat et al., 2024).

Conclusion

This study utilised acoustic simulation to investigate the acoustic performance of mosques equipped with two-loudspeaker systems under various architectural and occupancy conditions. The findings provide critical, practical insights for architects and mosque committees aiming to optimise the aural environment, particularly in small to medium-sized prayer halls.

The research established that the most significant determinants of acoustic quality are room volume,

ceiling material, ceiling shape, and occupancy, while the specific placement of the two loudspeakers (corner vs. center-front) had only a negligible practical effect on both the Speech Transmission Index (STI) and sound uniformity.

STI was found to be strongly and negatively correlated with room volume, and positively correlated with sound absorption from ceiling materials and occupancy. Larger volumes and reflective materials significantly reduce speech clarity due to reduced sound absorption within the room. Sound uniformity is negatively affected by room volume, pyramidal ceiling shapes, and the presence of high absorption from acoustic ceilings or full occupancy.

A robust acoustic design that maintains acceptable speech intelligibility ($STI > 0.5$) and sound uniformity ($SPL \text{ variation} \leq 6 \text{ dB}$) across both unoccupied and fully occupied conditions is achievable only when the mosque volume is limited to $1,125 \text{ m}^3$ or less. For larger volumes, a more sophisticated, distributed sound reinforcement system and advanced acoustic treatments are necessary to meet these criteria.

For the unoccupied condition, a maximum reverberation time of 2.5 seconds is recommended. This represents the critical limit necessary to ensure that STI remains above 0.5, which is suitable for complex messages with familiar context. The presence of a full congregation, acting as a substantial sound absorber, will naturally reduce reverberation time, thereby ensuring enhanced clarity and spiritual comfort during congregational prayers.

Acknowledgments

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АКУСТИЧЕСКАЯ ОЦЕНКА МЕЧЕТЕЙ С ДВУМЯ ГРОМКОГОВОРИТЕЛЯМИ: ВЛИЯНИЕ ГЕОМЕТРИИ, РАЗМЕРА, МАТЕРИАЛОВ ПОТОЛКА, РАСПОЛОЖЕНИЯ ГРОМКОГОВОРИТЕЛЯ И ЗАПОЛНЕННОСТИ ПОМЕЩЕНИЯ

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Аннотация

Введение. В данном исследовании представлено всестороннее изучение акустических характеристик мечетей, оборудованных двумя громкоговорителями, в различных условиях. Рассматривается распространенная проблема плохой акустики в индонезийских мечетях, которая часто является результатом архитектурных особенностей, выбора материалов и неоптимального проектирования звуковой системы. **Методы.** В ходе исследования с использованием акустического моделирования систематически варьировались несколько параметров: геометрия, размер молитвенной зоны (от 100 м² до 625 м²), материал потолка (акустическая плитка против гипсокартона), расположение громкоговорителей и уровень заполненности (пустое помещение против полностью заполненного). Основное внимание уделялось оптимизации индекса передачи речи (ИПР) для обеспечения разборчивости речи и равномерности уровня звукового давления (УЗД). **Ключевые результаты** показывают, что расположение громкоговорителей (в углу или в центре передней части зала) не оказывает существенного влияния ни на ИПР, ни на равномерность. Однако в больших залах (например, 3516 м³ и 6086 м³) наблюдались незначительные различия в равномерности звука (максимальный–минимальный УЗД) в зависимости от положения громкоговорителей. Напротив, объем помещения, материал потолка и уровень заполненности существенно влияют на ИПР; большие объемы и меньшее поглощение звука связаны с уменьшением четкости. На равномерность звучания также негативно влияют увеличение объема помещения и отражающие, сложные формы потолка (например, пирамидальные), тогда как повышенное поглощение может усилить доминирование прямого звукового поля, потенциально снижая равномерность. **Выводы.** Исследование показало, что для достижения ИПР > 0,5 и изменения УЗД < 6 дБ во всех условиях присутствия людей объем мечети не должен превышать 1125 м³. Кроме того, для обеспечения адекватной разборчивости речи (ИПР > 0,5) в условиях пустого помещения (худший случай) максимальное время реверберации (ВР) на частоте 1 кГц должно быть ограничено 2,5 секундами. Эти результаты предоставляют практические, основанные на фактических данных рекомендации по акустическому проектированию малых и средних мечетей в Индонезии.

Ключевые слова: мечеть, акустика помещения, громкоговорители, моделирование, равномерность звучания, индекс передачи речи.

URBAN IMPACTS ON VENTILATION IN HOT-HUMID CLIMATES: MULTI-HEIGHT BUILDINGS IN BASRA

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Abstract

The purpose of the study was to identify the most influential urban design factors for improving ventilation in the open spaces of multi-storey residential complexes in Basra's hot-humid climate. **Methods:** using a case study approach, we conducted ENVI-met v5.9 simulations for 16 models of two spaces within the "Al-Amal Residential Complex" during summer and winter. Four models reflected existing conditions, while 12 involved scenarios that adjusted building height, distance between buildings, and orientation, and were measured against environmental indicators: air temperature (T_a), wind speed (WS), sky view factor (SVF), and predicted mean vote (PMV). **Results** showed that building height is the most significant factor in improving ventilation and providing self-shading, followed by north-west orientation. Distance between buildings ranked last due to the trade-off between achieving urban breathing and increased solar exposure. The research recommends adopting compact vertical blocks with a north-west orientation and integrating vegetative or artificial shading to compensate for reduced self-shading and enhance social interaction.

Keywords: urban design factors; ventilation; multi-storey residential buildings; thermal comfort; ENVI-met; Basra.

Introduction

The outer urban spaces between residential buildings play a pivotal role as a vital connecting fabric of the built environment and as an attractive medium for social interaction among residents. However, the positive activation of these spaces requires the provision of thermal comfort that allows human presence in them throughout the day, summer and winter, especially in hot, humid climates where natural ventilation is a decisive factor in improving the microclimate.

It is clear from reviewing the previous studies that most of them investigated the influence of a single factor on outdoor space ventilation, while a few studies, such as Yola et al. (2022), began to explore the interaction between two factors (building height and canyon orientation). Although these studies contributed to an in-depth understanding of each factor, none of them provided a comparative assessment of three key design factors simultaneously — building height, distance between buildings, and building orientation- nor did they examine how these factors interact within an integrated urban context.

This knowledge gap is the starting point for this research. It examines the potential of urban standards to achieve effective natural ventilation in spaces between multi-storey residential buildings in Basra's specific climatic context, characterised

by hot, humid summers and mild winters with high relative humidity. The study aims to provide recommendations for urban designers to create environmentally successful urban spaces.

Therefore, the research will examine three urban design factors—building heights, distances between buildings, and building orientation—in improving ventilation in outdoor open spaces between multi-storey residential buildings in Basra's hot, humid climate.

Literature Review

This section represents the theoretical framework for the study, which includes two main parts, as shown in Fig. 1. The first part explores the interrelationships among the environmental indicators, including wind speed (WS), air temperature (T_a), sky view factor (SVF), and predicted mean vote (PMV) in hot-humid climates. The second part examines the role of urban design factors, including building height, distance between buildings, and building orientation in controlling outdoor ventilation and thermal performance.

Interrelationships among environmental indicators

In hot and humid climates, ventilation performance is directly related to environmental indicators on the one hand and to the distribution of buildings and street networks on the other hand. Surrounding buildings reduces WS around building blocks, and

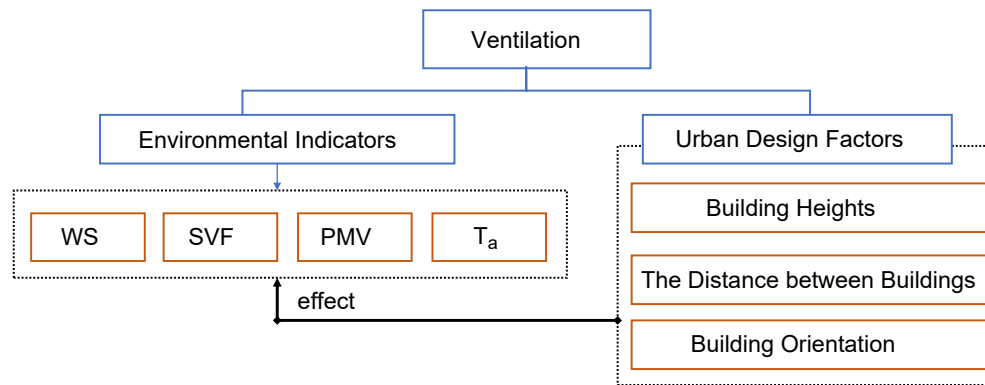


Fig. 1. The parameters identified in the theoretical framework (Source: Authors)

block height and road width affect wind pressure differences (Gülten and Öztop, 2020). Ambient temperature is considered the most influential environmental variable in hot regions, followed by sky view factor (SVF), and then the aspect ratio. Low SVF values would also help mitigate city air temperatures in high-density neighbourhoods during heatwaves (Fan et al., 2024). WS is the primary driver of natural ventilation and relief of high humidity.

Urban configurations that allow air to pass through, such as oriented buildings and courtyards, increase local WS. This increase enhances thermal comfort by generating evaporative cooling. The spaces between high-density buildings are characterised by thermal discomfort in summer due to reduced WS and air stagnation caused by these buildings, as obstacles (Palusci et al., 2022). A direct relationship exists between SVF and daytime heat gain: higher SVF values increase exposure to direct solar radiation. This will lead to raised T_a and surface temperatures. Low SVF values provide self-shading that protects the outer spaces from radiative thermal gain and keeps them cooler. Furthermore, the SVF can be controlled by adjusting the length-to-width ratio of a space to create shaded areas that prevent heat loss and promote passive heat storage in surfaces during winter. At the same time, these shaded areas reduce the effect of urban heat islands in summer (Pouri et al., 2025).

Afforestation elements play a decisive role in adjusting wind movement in hot, humid climates. A study by Dissanayake et al. (2023) compared different planting arrangements within square-shaped open spaces, and their results showed that the dispersed (random) planting pattern achieved the greatest improvement in average WS.

Ventilation is associated with both WS and shading that resulted from SVF reduction. Therefore, average WS between 1.5 and 3.6 m/s is preferable to reduce cold stress in winter, while 1.5 m/s is considered relatively calm in summer. These values vary with building height or environmental treatments (Abdalazeem et al., 2024). An increase in

WS also reduces physiological thermal stress at air temperatures below or above 35°C, depending on decreasing humidity (Bröde and Kampmann, 2023).

According to Musa et al. (2022), SVF optimally ranges from 0.38 to 0.65. Outdoors, in hot, humid climates, the acceptable PMV range is between −4 and +4. To achieve PMV moderation, WS must be high (1 to 2 m/s) to promote evaporative cooling, while reducing mean radiant temperature via shading elements, such as umbrellas, because direct solar radiation quickly raises the PMV value towards +3 or +4, and preferably, T_a should be between 24°C and 28°C with air movement (Bröde and Kampmann, 2023).

Urban design factors influencing natural ventilation

There are studies that investigated the influence of urban characteristics on natural ventilation at the urban level. Salem and Othman (2024) confirmed that the spaces between buildings were the most influential on ventilation quality, followed by the design of the street grid, and then by architectural building characteristics. Similarly, W. A. A. Mohamed (2022) concluded that street density is the dominant element in increasing the possibility of greater air permeation within residential complexes. This enhances the positive relationship between the openness of the urban fabric and the efficiency of natural ventilation.

Building heights: Height influences the vertical thermal gradient (Li and Donn, 2017). The average temperature decreases by 0.65 degrees Celsius for every 100 meters of height. This confirms the relationship between building height and local climate change. Yola et al. (2022) analysed the morphology of urban canyons (the space between buildings) in Kuala Lumpur (hot, humid climate). Their study found that increasing building height lowers the mean radiant temperature, especially in the morning and evening, but reduces WS inside the canyon when the increase is uniform on both sides. The study also noted the role of canyon orientation in modifying these effects. Consequently,

increasing the height-to-width ratio (H/W) positively affects the thermal environment by reducing thermal stress in the area. This is because it enhances shading and reduces the amount of solar radiation reaching the ground surface. Building height affects solar radiation, temperature, and WS. Elevations increase shading, which lowers the absorbed solar radiation and reduces the urban heat island effect. Tall buildings also act as thermal chimneys, drawing hot air upwards, away from the pedestrian level (Palusci et al., 2022).

By using ENVI-met simulations, Ragheb et al. (2024) demonstrated in their study in Egypt that building height significantly affects microclimatic conditions and pedestrian thermal comfort. They recommended that urban planners consider building heights and layouts to improve local climatic conditions. It has been noticed that the height-to-width ratio (H/W) affects T_a : a lower ratio increases solar absorption by road surfaces. That is why canyons with a lower H/W ratio are exposed to higher diurnal heat (Kareem and Mahmood, 2025) and ground surface temperatures are lower in higher-altitude residential buildings (Zheng et al., 2019). Salameh et al. (2023) noted in their study that the variety of building heights contributes to lower T_a than in moderate-contrast cases. Placing a high-rise next to a low building increases WS by up to 90 % while lowering the temperature by about 1 °C. Hence, the strategic integration of a limited number of high-rise buildings can enhance alley ventilation and reduce heat (Salameh et al., 2023).

Distance between buildings: Distance relates to “urban breathing”; it creates open spaces that allow airflow at pedestrian level. Therefore, integrating semi-open spaces with buildings significantly improves ventilation (Juan et al., 2021). However, a lower ground coverage ratio (10 %) increases annual solar radiation compared to a higher ratio (50 %), which provides greater shading (A. M. S. Mohamed, 2022). For thermal comfort, “semi-enclosed” spaces are preferred for daytime use, while “open” spaces are best for night time use (Lam and Hang, 2017). By design, scattered point layouts (wide spaces) are better ventilated for low site coverage, whereas closed styles with small distances suit very cold climates. The relationship between the building height and horizontal distance remains decisive for ventilation control (Ma and Chen, 2020). CFD-based studies have shown that ventilation performance is very sensitive to the spacing between buildings, since the maximum airflow is achieved when the separation distance is approximately equal to the height of the building, as both frontal and angular flows contribute to the movement of air around the building aggregates (Ghulam et al., 2021; Ayo and Mohd-Ghazali, 2024). The square spaces resulting from buildings’ setbacks of 8 m from the street and

16 m from corridors achieve better ventilation for both single- and multi-high-rise buildings (Xu et al., 2022).

Building orientation: Orientation is a pivotal factor in natural ventilation and solar radiation control in humid, hot areas, and aims to minimise thermal gain and maximise the effect of prevailing winds. Effective cross-ventilation depends mainly on the building’s orientation relative to the local wind direction (Mahmoud and Ghanem, 2019). Optimal orientation varies by climate, but in hot, humid regions, north-west orientation is often favourable (Abdelhafez et al., 2022). Moreover, the building form and orientation significantly influence the conditions of surrounding microclimates (Derakhshan and Karimimoshaver, 2026). Therefore, there is a need to make site-specific design decisions rather than following general rules, as orientations affect surface heat levels differently throughout urban contexts (Derakhshan and Karimimoshaver, 2026). At the urban level, tall buildings play a dual role depending on location. According to Lin et al. (2026), locating buildings in the western part slows prevailing winds (see Fig. 2, H2), while their location in the northern part (H3) reduces WS and increases airflow between buildings. Their placement in the north-western corner (H4) achieves balanced ventilation distribution by mitigating the decrease caused solely by western obstructions (Lin et al., 2026).

To summarise, previous studies emphasise the individual effects of building height, distance between buildings, and building orientation on natural ventilation and thermal comfort in hot-humid climates. Yet, their combined and comparative assessment remains unexplored. Most reviewed studies have focused on isolated variables or paired interactions (e.g., height with orientation), but none have examined the impact of all three factors within an integrated urban context, especially in a climate like Basra’s. Therefore, the current study’s comparative simulation approach is important to conduct. To carry out this comparison, it is necessary to use an accurate physically based climate simulation tool to assess the impact of three urban design factors on specific environmental indicators (WS, T_a , SVF, and PMV) that control ventilation quality. For this purpose, the ENVI-met v5.9 was chosen, a three-dimensional climate model based on fluid dynamics and thermodynamics that analyses airflow around and between buildings, along with radiation and heat exchange between surfaces and the atmosphere (Bruse and Fleer, 1998). However, the reliability of such a simulation largely depends on the accuracy and reliability of the model used. The effectiveness of the ENVI-met model in assessing thermal comfort and ventilation performance in outdoor spaces has been demonstrated in a growing body of research conducted in similar climates. One of

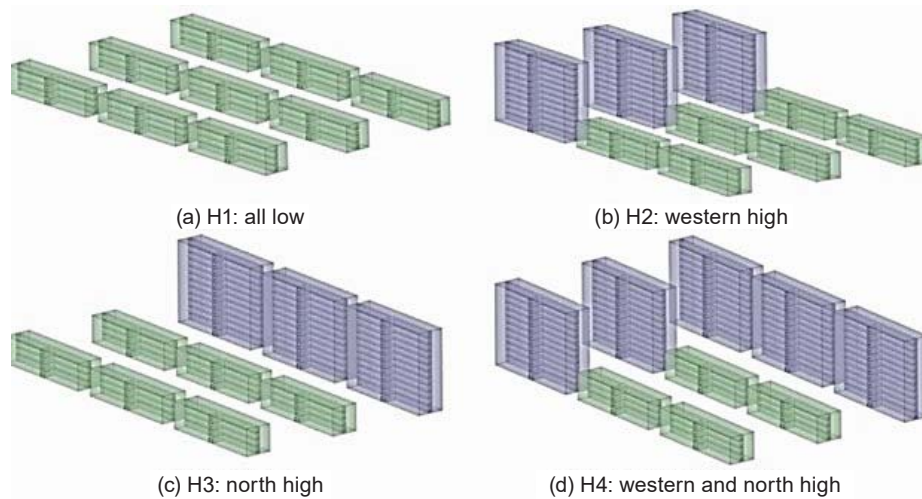


Fig. 2. The relationship between building height and orientation (Lin et al. 2026)

these applications is studies conducted in Basra (Almansor et al., 2026) and Baghdad (Ridha, 2022; Musa et al., 2023), as well as other hot-humid regions such as China (Ma and Chen, 2020; Liu et al., 2024; Schöneberger et al., 2025). Taken together, this evidence confirms the suitability of ENVI-met for use in this research.

Methods

The research examined the impact of three urban design factors — building heights, distance between buildings, and building orientation — on improving ventilation in outdoor spaces between multi-storey residential buildings in Basra city. To achieve this, a case study approach was adopted, selecting two sites within the Al-Amal residential complex in Basra city. Building on this selection, 16 models were simulated using ENVI-met v5.9 to assess the influence of these urban design factors under both summer and winter conditions. These models encompassed four base cases and 12 proposed models, representing three

distinct scenarios (see section 3.2 for more details). Numerical data from both case studies included four environmental indicators (WS, Ta, SVF, PMV) for summer and winter. For each of these scenarios, the mean of each environmental indicator was calculated in Excel. Delta (Δ) was calculated as the difference between the scenario and the base case, with the direction of improvement noted (see section 3.3). The study analysed numerical data and ENVI-met coloured maps both statistically and visually.

Case study selection

Basra city, the southernmost part of Iraq, is recognised for its extreme climatic conditions. Its climate is extremely hot and humid, with peak temperatures exceeding 50°C and scarce rainfall, posing serious challenges to achieving thermal comfort in outdoor urban spaces. Al-Amal residential complex, located in the north of Basra city (Fig. 3) was chosen as the field study area. The study selected two models of vertical building arrangements as

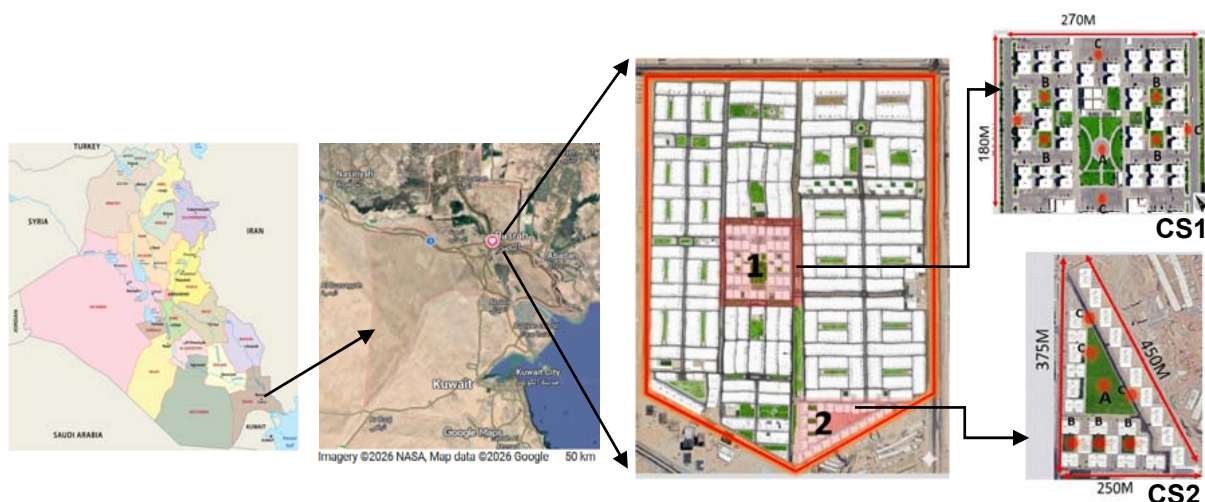


Fig. 3. The geographic location of case studies CS1 and CS2 (Annotated by the authors, source: Google Earth/Map)

case studies. This choice was made because they represent diverse urban patterns and block organisations, allowing for relatively generalized results in similar contexts. They are as follows:

- **Case Study 1 (CS1) (rectangular arrangement):** consists of 24 residential blocks with a height of four floors (G+3) with an area of 4.86 hectares. These blocks are organized in a symmetrical clustering around a wide central courtyard (Central Plaza), designed to promote social interaction, with small interspersed green spaces between the buildings, as shown in Fig. 3.

- **Case Study 2 (CS2) (triangular arrangement):** it is characterized by a different geometric configuration with an area of 4.68 hectares, where it includes 9 buildings with a height of seven floors (G+6) distributed according to a linear graded organization, in addition to 16 buildings with a height of four floors (G+4) distributed in an aggregate style. These elements converge around a large central area, with green spaces integrated into the assembly pattern, as shown in Fig. 3.

Simulation and scenario design

To achieve the research aim, the study conducted an environmental analysis of the two selected case studies (CS1 and CS2) by creating three-dimensional digital models using ENVI-met v5.9, an advanced tool for simulating local climate. The ENVI-met program was employed in this study to simulate the urban microclimate of complex urban environments on a sound physical basis. The program's proven reliability in thermal comfort aligns with local meteorological station data (Ridha, 2022), as evidenced by simulation outcomes, and has been verified across multiple hot-humid climates (see Section 2 for detailed sources). The model has

demonstrated acceptable accuracy in simulating wind speed and air temperature (Liu et al., 2024), which are essential indicators in the current study. Recent evaluations in subtropical and tropical contexts have shown that ENVI-met performs best during summer — the most important season for evaluating thermal comfort in Basra — when the model's results exhibit the fewest errors during this period (Liu et al., 2024). Due to the model's reliability in similar climatic contexts, it was chosen for the current research.

The modelling included all the constituent elements, including building blocks, vegetation, and the network of roads and sidewalks, to ensure accurate simulation of thermal interactions between surfaces and the atmosphere. To ensure simulations under the city of Basra's critical climatic conditions, data from the hottest and coldest days were selected from official meteorological data that represent the peak of climate extremes in Basra governorate for 2025 (Table 1 and Fig. 4). The simulation included extracting readings for four environmental indicators (WS, Ta, SVF, and PMV) at 15:00, as this time corresponds to the peak of daily heat stress. Nine receptors were strategically distributed in CS1 and eight in CS2 in three zones in each model to cover the morphological diversity: **Zone A** represented the central plaza; **Zone B** represented the spaces between buildings, and **Zone C** represented the area in front of buildings' entrances (see Fig. 5).

Three proposed scenarios were simulated in addition to the base case of each case study (BC-CS1, BC-CS2). Each of these scenarios involved four simulated models, with each pair related to a case study during summer and winter. In total, 16 proposed models were simulated (see Table 2).

Table 1. Daily climatic data used as input for ENVI-met simulations (extreme days in Basra, 2025) (Source: Basra Meteorological Office)

		Temperature		Wind		Relative Humidity	
		max	min	direction	m/s	min	max
Summer	11/07/2025	51	35.4	297°	3.1	7	22
Winter	2/02/2025	16.9	8	270°	2.8	40	90

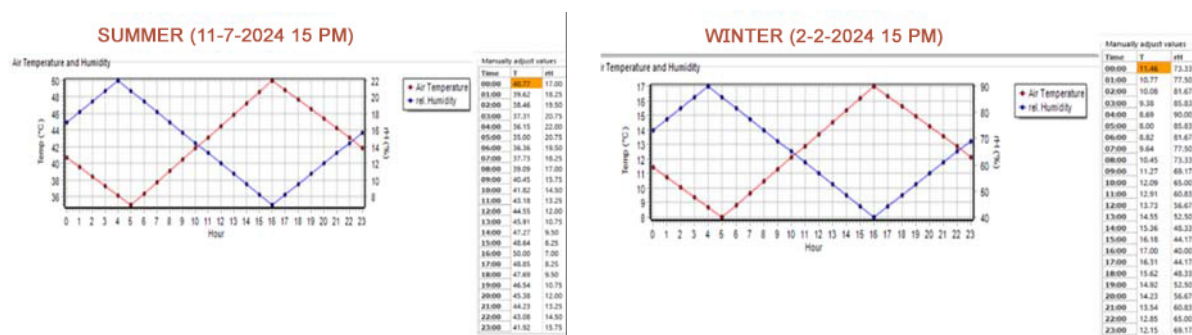


Fig. 4. Climatic inputs for the hottest and coldest day in Basra city in the ENVI-met program v5.9. (Source: Authors)

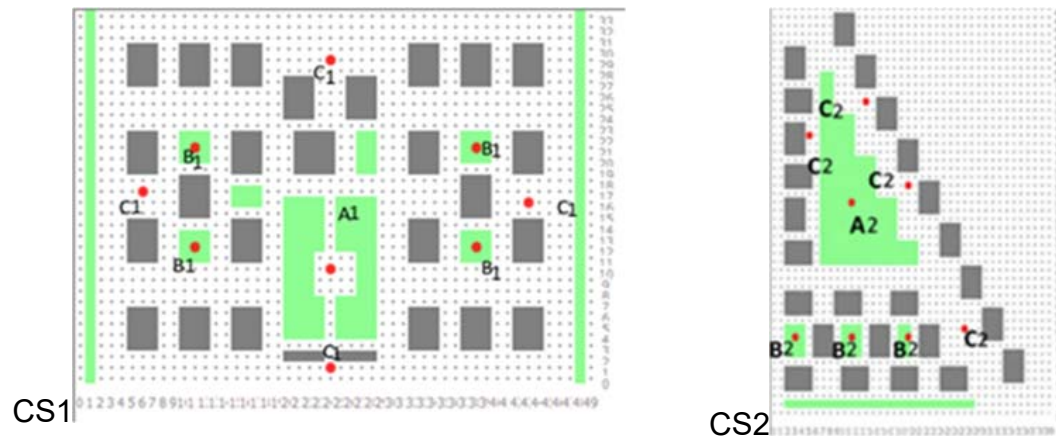


Fig. 5. 3D simulated digital model of CS1 and CS2 using the ENVI-met program v5.9. (Source: Authors)

Table 2. The abbreviation of the proposed simulated scenarios (Source: Authors)

	CS1		CS2	
Model	Summer	Winter	Summer	Winter
Base Case (BC)	BC-S1	BC-W1	BC-S2	BC-W2
Height (H-scenario)	H-S1	H-W1	H-S2	H-W2
Distance (D-scenario)	D-S1	D-W1	D-S2	D-W2
Orientation (O-scenario)	O-S1	O-W1	O-S2	O-W2

Each scenario examined one of the three selected urban design factors during summer and winter to isolate their impact as follows:

- **Increment height of buildings (H-scenario):** increasing the number of floors of buildings in CS1 and CS2 (+3), without changing orientation and distances between buildings. This amendment was selected to represent a moderate vertical expansion reflecting the common trends in residential density projects that align with Iraqi housing standards. This scale of change is substantial enough to affect shading, wind flow, and radiant heat exchange, enabling a robust evaluation of height-related effects.

- **Changing the distance between buildings (D-scenario):** increasing the distance between buildings in CS1 by two meters and decreasing it by two meters in CS2, without changing the original orientation and height. These changes were chosen because they may affect airflow dynamics and local climate characteristics in the region.

- **Changing orientation (O-scenario):** rotating building blocks towards the north-west direction without any change in height and distance between buildings. This direction was selected as it aligns with the favourable conditions of Iraq's hot, humid climate. It can substantially influence sun exposure and wind flow patterns.

Data analysis approach

The study used a quantitative method to identify which urban design factors most effectively improved ventilation in Basra, using statistical and visual

analysis. Improvement was defined as an increase in WS, a decrease in T_a , a decrease in SVF, and a decrease in PMV towards neutral. Delta values were normalised for comparison. The average improvement per scenario was calculated, and the results from both case studies were combined by calculating the arithmetic mean of the corresponding delta values from CS1 and CS2 for each indicator, ensuring equal weighting for both configurations. Statistical findings were supported by visual analysis of ENVI-met maps, comparing environmental indicator patterns, value ranges, and spatial distributions between the base case and scenario conditions.

Results

Statistical analysis

The study conducted a statistical analysis to identify the most positive influence of urban design factors (building height, distance between buildings, building orientation) on improving the natural ventilation by enhancing environmental indicators (WS, T_a , PMV, SVF) in outdoor open spaces of two different urban models (CS1 and CS2). The study determined the required improvement trend for each environmental indicator, as shown in Table 3, as mentioned in previous studies.

The analysis began by extracting four environmental indicators (WS, T_a , PMV, SVF) from ENVI-met for each receptor in the case studies. There were nine receptors in CS1 and eight in CS2. This process was repeated across three scenarios, plus the base cases, for both summer and winter. The

Table 3. The direction of improvement required for each environmental indicator (Source: Authors)

Indicator	Summer	Winter
WS	Increase (+)	Decrease (–)
T _a	Decrease (–)	Increase (+)
PMV	Decrease (–) to (0)	Increase (+) to (0)
SVF	Decrease (–)	Decrease (–)

arithmetic mean for each environmental indicator, scenario, and case study was calculated in Excel by averaging all receptor readings. For example, in summer, the WS readings of all nine CS1 receptors in the H-scenario were averaged. Table 4 shows the scenario means.

Next, the Delta (Δ) value for each environmental indicator and scenario was calculated in Excel. The desired optimisation direction for each indicator was checked using Table 3. If an increase was the target for an indicator, the Delta was calculated as:

$$\delta = \text{Mean}_{\text{Scenario}} - \text{Mean}_{\text{BC}}$$

And if a decrease was the target for an indicator, the Delta was calculated as:

$$\delta = \text{Mean}_{\text{BC}} - \text{Mean}_{\text{Scenario}}$$

Because environmental indicators differ in units and ranges, each indicator's Δ values (for H-, D-, O-scenarios) were normalised in Excel using linear normalisation and the following equation:

$$\delta_{\text{normal}} = (\delta - \delta_{\min}) / (\delta_{\max} - \delta_{\min})$$

This normalisation process produced Δ_{normal} values ranging from 0 to 1 for each environmental indicator in each scenario, where 1.00 represents the best relative performance and 0.00 the worst. For each scenario (H, D, O), the arithmetic mean of all seven environmental indicators' Δ_{normal} values was calculated using Excel's AVERAGE function. Table 5 shows the calculated Δ for each indicator and scenario in both case studies for clarity.

Table 6 shows a consolidated view in which higher values indicate greater improvement, and lower values indicate less improvement or deterioration.

To find which urban design factor has the greatest positive impact, the scenarios were ranked in descending order by the average Δ_{normal} for each case study. The overall mean for each scenario across both case studies was then recalculated using the AVERAGE function to determine which urban design factor had the greatest overall positive effect (Table 7).

Visual analysis of simulation maps

The visual analysis of the extracted coloured maps for the four environmental indicators in the base case of CS1 and CS2, and the proposed scenarios, compared the colour distribution of what happened in Zones A, B, and C, as follows:

The base cases analysis (CS1 & CS2). The base-case results for CS1 showed that WS reached up to 3.08 m/s in summer, and 3.30 m/s in winter, while in CS2, the maximum WS was 3.42 m/s in summer and 2.80 m/s in winter. The highest values

Table 4. Arithmetic mean for each indicator and for each scenario in CS1 and CS2 (Source: Authors)

Indicator	CS1				CS2			
	BC	H	D	O	BC	H	D	O
WS -Summer	1.331	1.344	0.882	1.256	0.473	0.666	0.766	0.843
WS -Winter	1.136	1.220	0.786	1.186	0.741	0.690	1.435	0.788
T _a -Summer	48.531	48.372	48.417	48.333	48.493	48.254	48.538	48.358
T _a -Winter	16.294	16.188	16.196	16.149	16.278	16.175	16.130	15.829
PMV- Summer	8.002	8.081	8.243	8.013	8.165	7.026	8.096	7.261
PMV- Winter	–0.419	–1.011	–0.546	–0.513	–1.155	–1.081	–1.079	–0.701
SVF	0.868	0.742	0.831	0.869	0.731	0.629	0.813	0.731

Table 5. Delta Δ values (with the direction of improvement) for CS1 and CS2 (Source: Authors)

Indicator	CS1			CS2		
	H	D	O	H	D	O
WS -Summer	0.013	–0.449	–0.076	0.1938	0.294	0.370
WS -Winter	–0.084	0.350	–0.050	0.051	–0.694	–0.046
T _a -Summer	0.159	0.114	0.198	0.239	–0.045	0.134
T _a -Winter	–0.107	–0.099	–0.146	–0.102	–0.147	–0.448
PMV- Summer	–0.078	–0.241	–0.011	1.139	0.069	0.904
PMV- Winter	–0.592	–0.126	–0.094	0.074	0.076	0.454
SVF	0.126	0.037	–0.001	0.101	–0.082	0.000

Table 6. The average Delta for each scenario across environmental indicators (Source: Authors)

Indicator	CS1			CS2		
	H_norm	D_norm	O_norm	H_norm	D_norm	O_norm
WS -Summer	**1.000	*0.000	0.808	0.000	0.567	**1.000
WS -Winter	*0.000	**1.000	0.079	**1.000	*0.000	0.869
T _a -Summer	0.533	*0.000	**1.000	**1.000	*0.000	0.632
T _a -Winter	0.833	**1.000	*0.000	**1.000	0.870	*0.000
PMV- Summer	0.708	*0.000	**1.000	**1.000	*0.000	0.781
PMV- Winter	*0.000	0.935	**1.000	*0.000	0.007	**1.000
SVF	**1.000	0.298	*0.000	**1.000	*0.000	0.448
Average	0.582	0.462	0.555	0.714	0.206	0.676

* Worst Performance

** Best Performance

Table 7. Total mean for each scenario across both case studies (Source: Authors)

Indicator	CS1	CS2	Total Mean
H	0.582	0.714	0.648
O	0.555	0.676	0.616
D	0.462	0.206	0.334

in both cases were concentrated in **Zone C** (facing west), followed by **Zone A**, while the lowest values were recorded in **Zone B** (see Fig. 6). For the SVF, **Zone A** emerged as the most open to the sky, followed by **Zone B**, while **Zone C** recorded the minimum values in CS1. In CS2, **Zone A** remained the leader, but **Zone C** recorded the second-highest SVF values, and **Zone B** recorded the lowest SVF (most shaded). As shown in Fig. 6, PMV in CS1 ranged widely (5.85–8.43 in summer, –1.65–0.22 in winter). The highest values were concentrated in **Zones A** and **B**, and the lowest in **Zone C**. CS2 followed a similar pattern (5.69–8.31 in summer, –1.82–0.05 in winter), with **Zone A** having the widest PMV range. Regarding Ta, the highest readings in CS1 (up to 49.34°C in summer) were concentrated in the western part across **Zones B** and **C** during both seasons; **Zone A** recorded the lowest T_a values in winter. In CS2, the highest T_a values were concentrated in **Zone C**, followed by **Zone A** and then **Zone B**, in both summer and winter (Fig. 6).

Simulation of the proposed scenarios

Increasing building height scenario. Compared to the base case (Fig. 7), increasing building height led to higher WS in both case studies during summer, especially in **Zone B** and eastern **Zone C**, with the highest recorded WS reaching 3.29 m/s in CS1 and 4.03 m/s in CS2. However, WS decreased in winter for CS2 (dropping to 2.87 m/s), while it slightly increased to 3.71 m/s in CS1, especially in **Zones B** and **C**. SVF values decreased in both case studies, resulting in post-scenario ranges of 0.36–0.93 for CS2 (the greatest reduction) and 0.40–0.94 for

CS1. The decrease was concentrated in **Zones C** and **B** and at the edges of **Zone A**. Regarding PMV, although thermal comfort remained above the acceptable upper limits (+4), the values decreased in summer across both case studies (down to 5.58 in CS1 and 5.42 in CS2), especially in **Zones B** and **C**. In winter, the PMV increased slightly, with the rise concentrated in **Zones C** and **B**. As for Ta, the readings showed a very slight reduction (less than 0.3 °C) across all examined zones in both summer and winter (Fig. 7).

Changing the distance between buildings scenario. In this scenario, the distance between buildings was reduced in CS1 from 12 m to 10 m, and increased in CS2 from 8 m to 10 m. As a result, WS in CS1 decreased by 0.11–2.65 m/s in summer and by 0.09–2.58 m/s in winter when the distance between buildings was reduced, especially in **Zones B** and **A**; however, in **Zone C**, the WS gradient increased (Fig. 8). In CS2, a very slight increase in WS was observed across all zones, with values reaching 0.07–4.36 m/s in summer and 0.20–3.01 m/s in winter. According to Fig. 8, SVF in CS1 decreased to 0.32–0.86, concentrating in **Zones B** and **C**, while **Zone A** changed only at its edges. In CS2, SVF values increased to 0.50–0.93. The rise was concentrated in **Zone C**, and at the boundaries of **Zone A**. PMV values in CS1 decreased in summer to 5.77–8.38 across all Zones, and rose slightly in winter (–1.58–0.06). In CS2, the increase in distance led to higher PMV values (5.77–8.31 in summer, –1.86 to –0.10 in winter), especially in **Zones B** and **C**. **Zone A** showed no significant change. T_a decreased slightly in CS1 (summer: 47.42–48.11; winter: 15.66–16.54) across all zones. However, in CS2, a very slight increase was observed (summer: 47.48–49.34; winter: 15.65–16.59) across all zones.

Changing building orientation scenario. In this scenario, the orientation of both case studies was changed to the North-West. From the simulation results (Fig. 9), WS increased in CS1, with values reaching up to 2.5 m/s in summer and 2.7 m/s

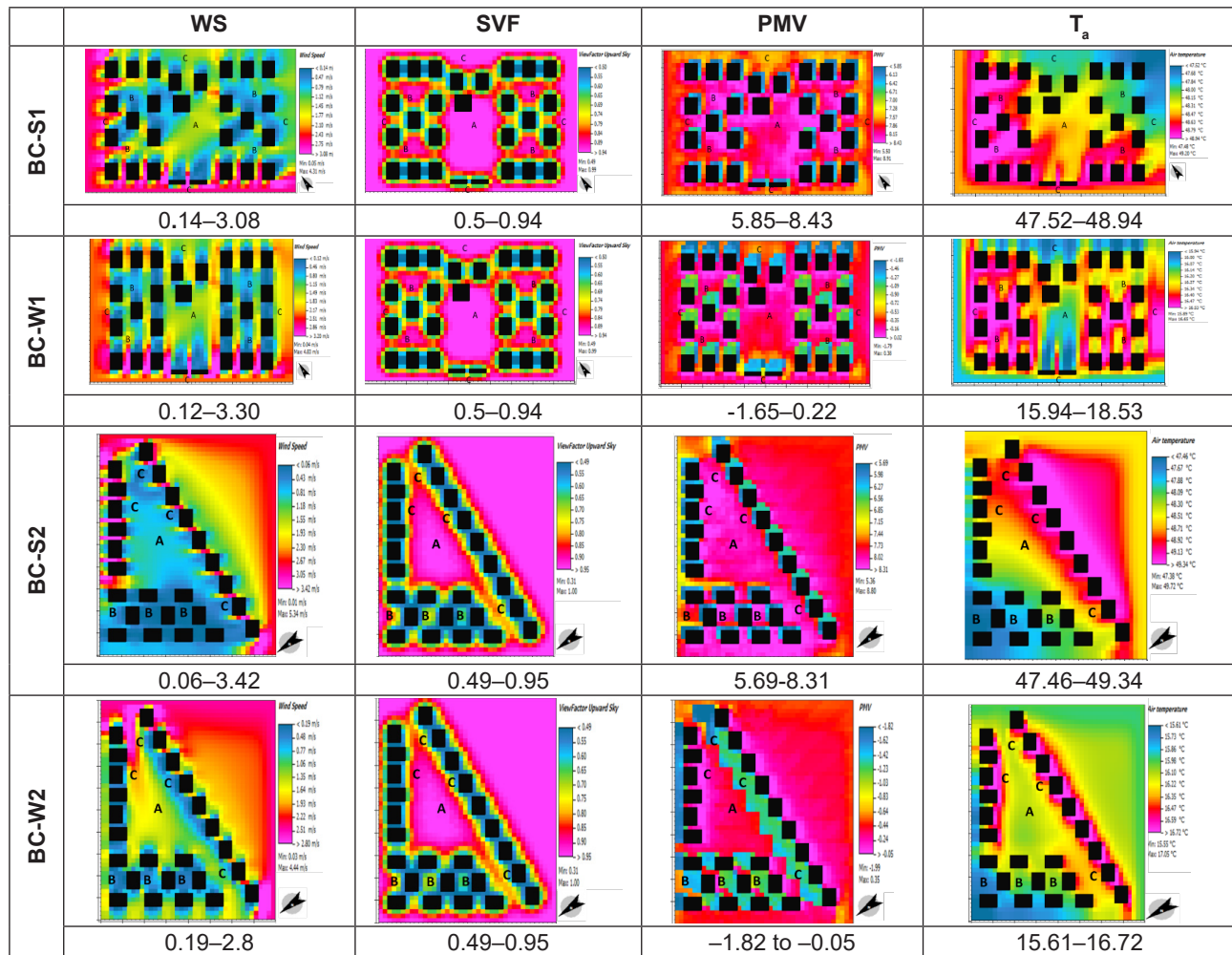


Fig. 6. Simulated maps of WS, SVF, PMV, and T_a generated by ENVI-met for the BC-CS1 and BC-CS2 at 15:00 (Source: Authors)

in winter, reflecting the spatial distribution between the eastern and western zones, while **Zone A** had no change. In CS2, the WS increased across **Zones A** and **C**, reaching the values up to 4.34 m/s in summer and 4.25 m/s in winter. SVF showed no change in either summer or winter in both case studies. Regarding PMV, the readings increased in summer (5.88–8.46 in CS1; 5.87–8.20 in CS2) and decreased in winter (CS1: -1.77 to -0.88; CS2: -1.94 to -0.08), reflecting similar spatial distributions in both case studies. T_a readings in CS1 rose slightly in summer (concentrated in eastern **Zone C**) and decreased in winter (observed in western **Zone C**), with changes of 0.3–0.4 °C. However, in CS2, T_a decreased slightly in summer and winter (by roughly 0.1–0.2 °C). This decrease was observed in **Zone B** (Fig. 9).

Discussion

Visual analysis of simulation maps for four environmental indicators in both case studies shows a close connection between urban design factors and climate performance. SVF is the main driver of temperature variation and thermal comfort. The

central plazas (**Zone A**) recorded the highest SVF values (CS1: 0.94; CS2: 0.95), making them focal points for solar radiation accumulation. In these areas, PMV reached very critical levels in summer (CS1: 7.86–8.4; CS2: 7.73–8.02) and varied seasonally. In winter, rapid heat loss due to night radiative cooling of the open sky made them the coldest zones. In contrast, building entrances (**Zone C**) and interbuilding spaces (**Zone B**) provide ‘mass shading’ which successfully reduces thermal stress. The WS enhanced natural ventilation (3.42 m/s). However, the impact of wind on T_a depends on the source of the air mass. For instance, in Basra’s climate, where hot, dry north-westerly winds are prevalent, increasing WS may raise T_a through convection before achieving physiological cooling. These findings show that outdoor open spaces in both case studies experience sharp thermal fluctuations and high SVF. This highlights the need to modify the schematic to improve environmental indicators and ventilation. Therefore, the current study proposes scenarios for three urban design factors—height, distance between buildings, and

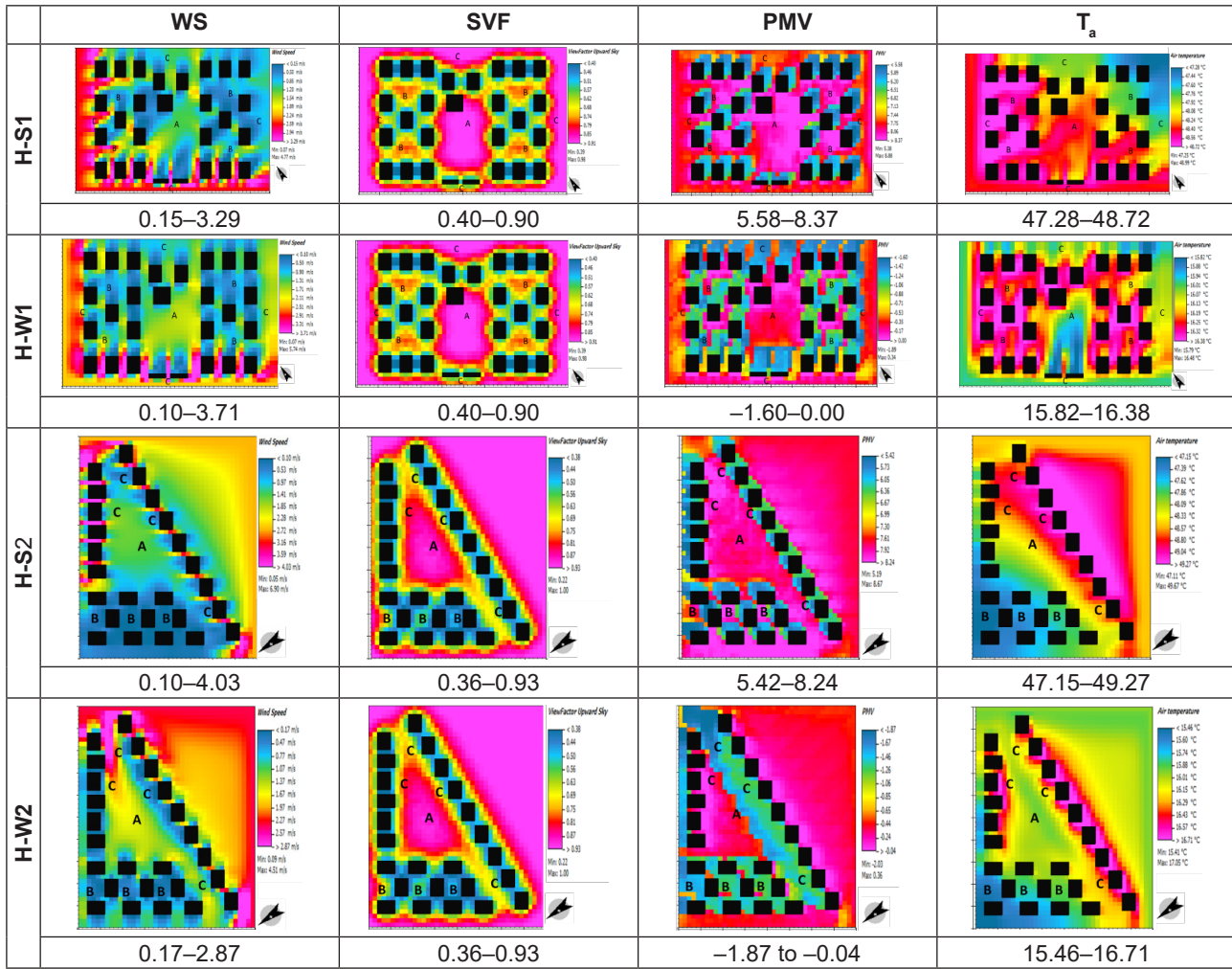


Fig. 7. Simulated maps of WS, SVF, PMV, and T_a generated by ENVI-met of the height scenario of CS1 and CS2 at 15:00 in summer and winter (Source: Authors)

building orientation — to determine which has the most positive effect on ventilation, aiming to generalise findings to similar spaces.

The statistical analysis, using the normalised Delta values as described in section 4.1, which adjusts differences to a common scale to allow comparison, was used to evaluate improvements in environmental indicators and to provide a clear ranking of urban design factors influencing ventilation. The most influential factor was building height, followed by building orientation, and then distance between buildings. This ranking was consistent in all case studies, as shown in Table 7. The statistical analysis for the building height factor indicated an improvement of 0.648. This finding aligned with visual analysis results, which demonstrated marked improvements in environmental indicators for both study cases. It was observed that vertical expansion led to an increase in air pressure at the building entrances (**Zone C**), in the interbuilding spaces (**Zone B**), and at the edges of the central plaza (**Zone A**). Thus, air velocities increased during the

summer season. This dynamic reversed in winter, which led to reduced thermal stress and improved physiological cooling in hot, humid conditions. This finding highlighted the influence of building height on environmental performance, supporting the findings of Lin et al. (2026) in a comparable urban context. It also aligns with the findings of Ragheb et al. (2024) study in Egypt's hot-arid climate, suggesting that the positive effect of building height on ventilation and thermal comfort may be observed across different hot-climate types. This scenario also supported the buildings' role as thermal chimneys that draw hot air upwards, in line with Palusci et al.'s (2022) study.

The visual map analysis also revealed decreased SVF values in both summer and winter, leading to increased mutual shading at interbuilding spaces (**Zone B**), building entrances (**Zone C**), and the central plaza edges (**Zone A**). This shading contributed to reducing the levels of solar radiation, which reduced the effect of heat islands by forming cool air pockets at entrances (**Zone C**), and slightly decreased PMV in summer while increasing it in

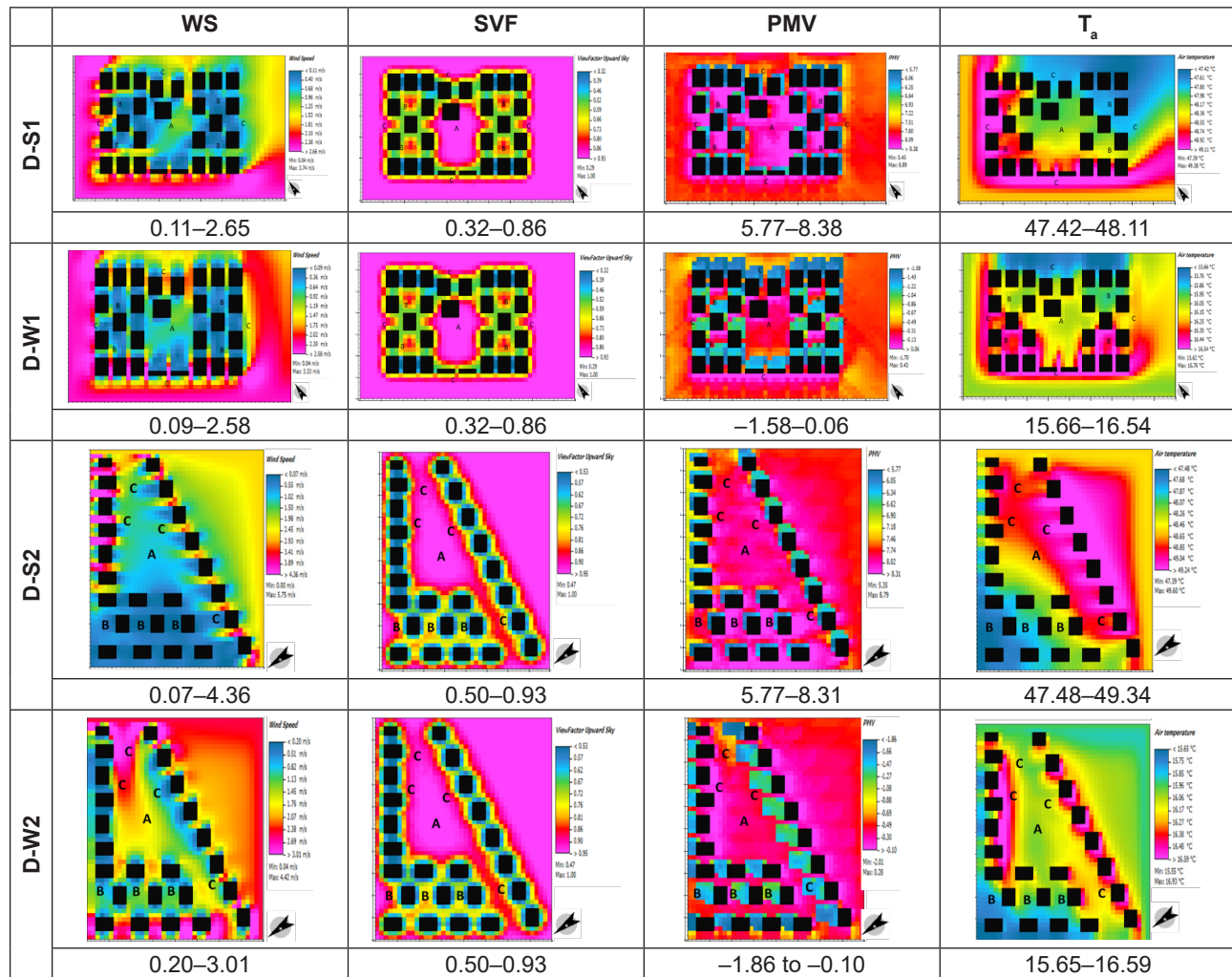


Fig. 8. Simulated maps of WS, SVF, PMV, and T_a generated by ENVI-met of the distance scenario for CS1 and CS2 at 15:00 in summer and winter (Source: Authors)

winter, thereby reducing heat loss. These results align with Zheng et al. (2019), who found that taller buildings yield lower surface temperatures due to increased shading. This can explain reduced summer air temperatures in CS2 zones: interbuilding spaces (**Zone B**) and at building entrances (**Zone C**) compared with those in CS1. This may be because building height diversity in CS2 helps lower air temperatures compared to designs with less contrast in CS1, as found in Salameh et al.'s (2023) study. This finding is consistent with those of Pouri et al. (2025), who demonstrated that modifying aspect ratios to control SVF can moderate surface heat loss and enhance passive heat storage.

Statistical analysis showed that building orientation ranked second, with an improvement margin of 0.616. This result matches the visual analysis, which showed that orientation change improved WS in CS1 in both summer and winter, with improvement at building entrances (**Zone C**) and the central plaza (**Zone A**). In CS2, improvements were observed only in winter and were limited to

the building entrances (**Zone C**), attributable to their position relative to prevailing winds, and also occurred in interbuilding spaces (**Zone B**) and at the boundaries of the central plaza (**Zone A**). These results are consistent with those of Mahmoud and Ghanem (2019), who studied the role of orientation in cross ventilation. The visual analysis also showed that the stable SVF value across seasons in both case studies indicates that orientation alone does not affect thermal radiation rates, unless combined with changes in block shape or open-space configuration. Regarding thermal effects, values of both T_a and PMV increased in summer in both case studies: the increase was widespread in CS1 and concentrated in the central plaza (**Zone A**) in CS2, due to heat gain from dry, hot winds and altered facade solar exposure angles. These results are in line with those of Mahmoud and Ghanem (2019), confirming the importance of orientation for thermal performance. The observed site-specific variation in surface heat levels supports the argument of Derakhshan and Karimimoshaver (2026) that orientation effects

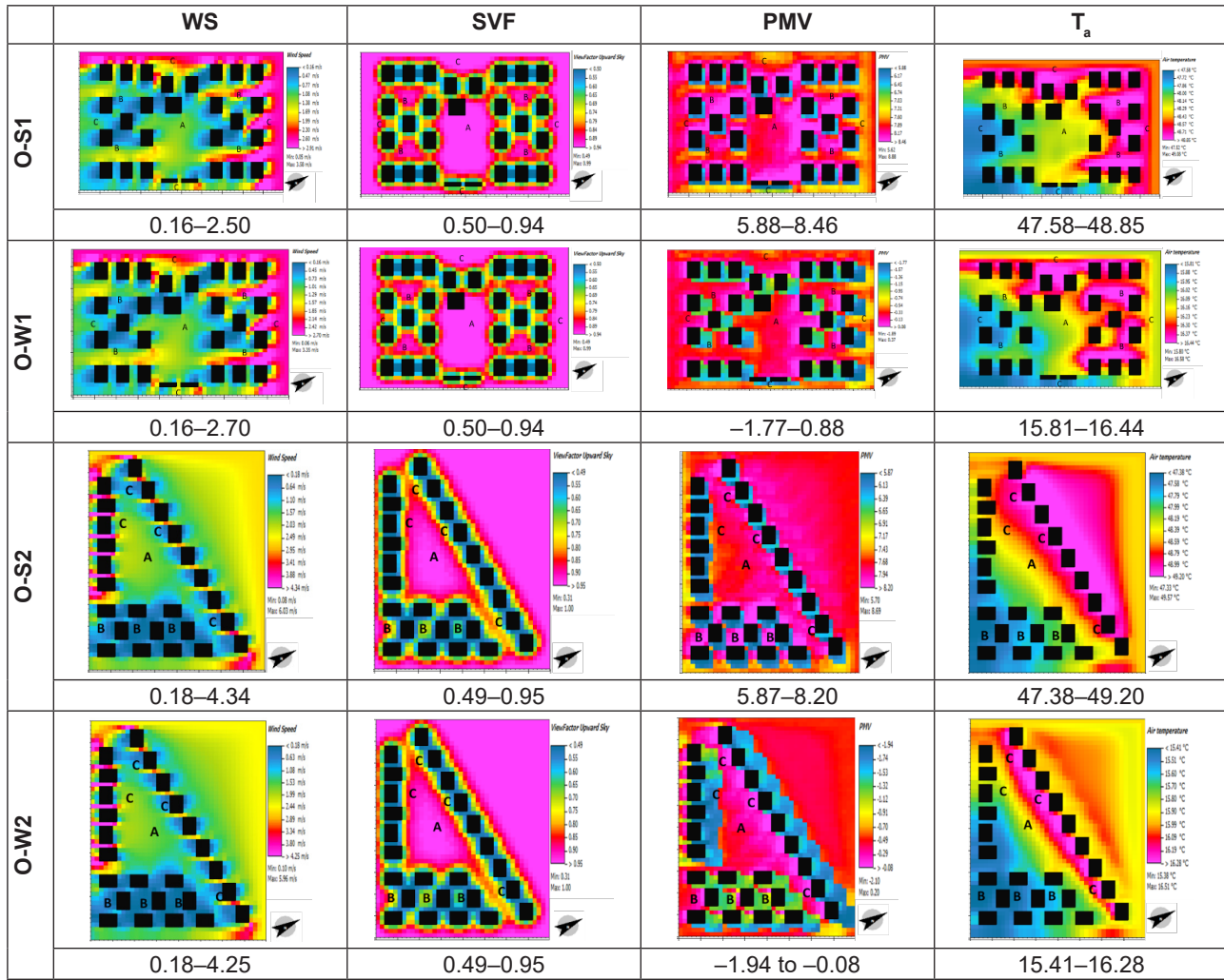


Fig. 9. Simulated maps of WS, SVF, PMV, and T_a generated by ENVI-met of the orientation scenario for CS1 and CS2 at 15:00 in summer and winter (Source: Authors)

cannot be generalised. It is important to highlight the role of the north-west orientation in improving ventilation in both case studies (Abdelhafez et al., 2022). This aspect corroborates the findings of Lin et al. (2026), whose research showed that orientation promotes an equitable distribution of ventilation. However, the promotion of thermal comfort through orientation remained subject to the combined effects of WS and radiation, as they related to orientation and urban morphology in both case studies. Therefore, urban designers should employ an integrated approach that balances ventilation and solar radiation in hot, humid climates.

The results showed that changes in the distance between buildings ranked third in optimisation efficiency, with a difference of 0.334. A visual analysis further revealed an inverse relationship between “urban breathing” and thermal radiation protection. Mass convergence in CS1 caused air stagnation in interbuilding spaces (**Zone B**) and at building entrances (**Zone C**). This effectively lowered the SVF value, reduced thermal stress, and improved

PMV and T_a during summer daylight hours. This is supported by the findings of Mahmoud and Ghanem (2019) and Fan et al. (2024) in the same section of their studies, which recommended prioritising shading in hot climates. In contrast, greater distances between buildings in CS2 promoted airflow, aligning with the urban breathing concept (Juan et al., 2021). This also confirms the CFD-based findings of Ghalam et al. (2021) and the numerical simulations of Ayo and Mohd-Ghazali (2024), who revealed the effectiveness of the distance between buildings on ventilation performance. However, the greater distances between buildings could increase annual solar radiation and T_a, and in turn, increase PMV and SVF. Accordingly, a design balance between ventilation and heat protection is required. Thus, semi-closed layouts are more suitable for hot daytime conditions, while sparse layouts cool more efficiently at night (Lam and Hang, 2017).

Conclusion

The research examined the impact of three urban design factors (building heights, the distance

between buildings, and building orientation) on improving ventilation in outdoor open spaces between multi-storey residential buildings in the hot, humid climate of Basra city. This aim was achieved by applying a case study approach along with statistical and visual analysis. The study simulated 16 models, four of which represented the base case for two case studies in summer and winter, and 12 were proposed models under three scenarios: increment height of buildings (H-scenario), changing the distance between buildings (D-scenario) or changing orientation (O-scenario). The statistical results, supported by visual analysis, indicated that the most influential factor in improving the environmental indicators examined in the two case studies was building height, followed by orientation, and then distance between buildings.

1. Building height was the most effective factor for achieving natural ventilation in hot, humid climates such as Basra city, both in summer and winter, because increasing building height transforms the urban fabric from a radiant receiver to a mutual shading system. This reduced winter heat loss by lowering cold wind speeds and raising PMV values towards the winter comfort zone, thereby achieving "improved seasonal thermal performance".

2. Orientation took second place in improving ventilation. Despite its importance in breaking the state of "air stagnation" and increasing wind speed, the trade-off was a slight increase in T_a due to convective heat gain from hot winds, but it did not change the SVF values. This means that the area exposed to sunlight was not changed in summer and winter. Therefore, to achieve maximum ventilation efficiency in Basra city, effective solutions and treatments must be identified for both seasons to support environmental sustainability. A pattern

of vertical blocks oriented north-west should be implemented to meet radiation protection standards and the minimum urban breathing requirements.

3. The distance between buildings factor revealed a design trade-off requiring a balance between ventilation and shading. Increasing the distance between buildings benefited urban ventilation, but it also made the spaces more exposed to solar radiation and to higher PMV values. Accordingly, the study suggested that vertical stacking method for mutual shading can be the best design strategy for Basra city. This strategy can reduce thermal stress and improve the physiological comfort of pedestrians when temperatures exceed 48°C.

4. There is a need to identify environmental treatments to improve the currently studied outdoor open spaces and similar ones that are exposed to sunlight and experience high PMV values. It is recommended to use artificial or plant shading elements in courtyards with dimensions greater than 10–12 meters to compensate for the lack of self-shading by buildings.

5. This study offers an analytical framework for similar urban spaces, provided that it aligns with the city of Basra's urban and climatic context, characterised by high summer temperatures (>48°C), high humidity, the dominance of north-westerly winds, and a medium to high-density urban fabric of multi-storey residential buildings. It is recommended that the same methodology be re-applied in other climate contexts to test the extent to which the results can be generalised more widely.

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ВЛИЯНИЕ ГОРОДСКОЙ ЗАСТРОЙКИ НА ВЕНТИЛЯЦИЮ В УСЛОВИЯХ ЖАРКОГО И ВЛАЖНОГО КЛИМАТА: МНОГОЭТАЖНЫЕ ЗДАНИЯ В БАСРЕ

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Аннотация

Цель исследования заключалась в выявлении наиболее значимых факторов градостроительного проектирования, способствующих улучшению вентиляции открытых пространств в многоэтажных жилых комплексах Басры, климат которой характеризуется высокой температурой и влажностью. **Методы:** на примере жилого комплекса «Аль-Амаль» было проведено моделирование в программе ENVI-met (версия 5.9) для 16 вариантов двух участков территории в летний и зимний периоды. Четыре модели отражали существующие условия, а 12 других представляли собой сценарии с варьированием высоты зданий, расстояния между ними и их ориентации; оценка проводилась по таким показателям, как температура воздуха (T_a), скорость ветра (WS), коэффициент видимости неба (SVF) и прогнозируемая средняя оценка теплового комфорта (PMV). **Результаты** показали, что высота зданий является наиболее значимым фактором для улучшения вентиляции и обеспечения эффекта самозатенения; за ней следует ориентация зданий по оси северо-запад. Расстояние между зданиями оказалось наименее значимым фактором из-за необходимости искать компромисс между обеспечением аэрации («дыханием» городской среды) и увеличением уровня инсоляции. В исследовании рекомендуется использовать компактные высотные блоки, ориентированные на северо-запад, а также применять элементы озеленения или искусственные навесы для компенсации снижения эффекта самозатенения и стимулирования социального взаимодействия.

Ключевые слова: факторы градостроительного проектирования; вентиляция; многоэтажные жилые здания; тепловой комфорт; ENVI-met; Басра.

IMPACT OF ROOM HEIGHT ON HEAT TRANSFER EFFICIENCY IN VARIOUS HEATING SYSTEMS: A NUMERICAL ANALYSIS

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Abstract

The purpose of the study. This study investigates the impact of varying room heights on the heat transfer efficiency of heating systems, specifically comparing conventional radiator-based heating with underfloor heating. **Methods.** Using Computational Fluid Dynamics (CFD) simulations, we analysed temperature distributions at three ceiling heights (2.7 m, 3 m, and 3.3 m). The numerical model was used to examine airflow behaviour, thermal stratification, and temperature variation within the occupied space under different heating conditions. **Results.** The results indicate that lower room heights tend to reduce vertical temperature stratification, thereby increasing the overall perceived temperature, while taller rooms exhibit greater temperature gradients between the floor and ceiling. The simulations also show that the location and mode of heat delivery have a substantial influence on indoor temperature distribution. Furthermore, underfloor heating systems demonstrated superior thermal uniformity and energy efficiency compared to radiator-based systems by distributing heat more evenly across the lower occupied zone. **Conclusions.** These findings contribute to optimizing energy efficiency and occupant comfort in building design by tailoring heating strategies to specific room dimensions. The study also highlights the importance of considering room geometry alongside heating-system selection when evaluating indoor thermal performance and developing energy-conscious design solutions for enclosed indoor spaces.

Keywords: floor heating, heat transfer, natural displacement, computational fluid dynamics.

Introduction

Energy consumption has increased significantly over the past few decades, primarily driven by industrial growth and rapid urbanisation, which have led to the proliferation of buildings and infrastructure. In Iran, this situation is exacerbated by low energy prices, which contribute to inefficient energy use and a lack of motivation for energy conservation practices among consumers and businesses (Tol and Madessa, 2024; Ghahramani et al., 2020). In contrast, many non-oil-producing countries have implemented stringent regulations aimed at improving energy efficiency in building design and heating systems. These regulations focus on optimising energy use to minimise waste and enhance the sustainability of building operations (Cui, 2024; Stern et al., 2001).

A critical consideration in modern building design is the distribution of heat, which directly impacts both energy efficiency and occupant comfort. Among the various heating systems available, underfloor heating (UFH) and radiator-based heating are frequently studied due to their differing operational

characteristics and efficiency profiles. Recent studies have shown that UFH systems provide more consistent thermal comfort by distributing heat more evenly across the room, significantly reducing temperature stratification — where warm air accumulates near the ceiling, leaving cooler air at lower levels. This stratification is particularly problematic in buildings with high ceilings, as pronounced vertical temperature gradients can lead to discomfort and increased energy costs when occupants adjust thermostats to achieve a suitable environment (Ghahramani et al., 2020; Koca et al., 2014; Tol and Madessa, 2024). For instance, occupants in a 2.7-metre-high room may experience a higher perceived temperature due to reduced thermal stratification, whereas taller rooms could exhibit larger gradients that detract from comfort.

Research indicates that UFH systems can reduce energy consumption by operating at lower temperatures compared to traditional radiator systems. For example, Koca et al. (2024) emphasise that integrating UFH with low-temperature heat pumps can enhance energy efficiency and indoor

air quality (Koca et al., 2014). Furthermore, Haslinger et al. (2021) provide insights into validation techniques used in computational fluid dynamics (CFD) simulations of heating systems, underscoring the importance of accurate modelling in predicting thermal performance (d'Adamo et al., 2021). Understanding and mitigating temperature stratification through effective heating design is crucial for modern buildings, especially as energy costs rise and environmental concerns become more pressing. Therefore, incorporating advanced heating technologies such as UFH can play a significant role in achieving sustainable building practices (Iranzo, 2019; Stern et al., 2001).

Previous studies have focused on improving heating efficiency in residential buildings, particularly in colder climates where heating energy consumption is high. However, the scientific gap this paper addresses lies in the need for a more detailed analysis of temperature distribution across different room heights and heating systems. This study aims to provide a numerical simulation of temperature gradients in rooms with varying ceiling heights (2.7 m, 3.0 m, and 3.3 m), using both radiator and underfloor heating systems, to determine which system achieves superior thermal comfort and energy efficiency. Moreover, this paper intends to fill the gap in recent comparative studies, as many existing studies are either outdated or do not focus on the interaction between room height and heating system performance.

Moreover, the impact of ceiling height on room temperature distribution was investigated at heights of 3.3 m, 3.0 m, and 2.7 m. The findings suggest that reducing ceiling height could improve perceived temperature, as rooms with lower ceilings tend to maintain a more uniform temperature distribution. For instance, occupants in a 2.7-metre-high room may experience a higher perceived temperature due to reduced thermal stratification. Research continues to emphasise that low-temperature heating systems, such as heat pumps, enhance energy savings by minimising efficiency losses and improving thermal comfort (Koca et al., 2014; Cui, 2024).

Recent studies have shown that low-temperature heating systems, when paired with modern heat pumps, offer significant advantages in maintaining indoor comfort while improving energy efficiency. The use of such systems allows for better integration with renewable energy sources, such as solar panels, and reduces reliance on conventional fossil fuels (Tol and Madessa, 2024). Additionally, the combination of underfloor heating with low-temperature systems has been shown to improve indoor air quality and occupant comfort, leading to more widespread adoption in both residential and public buildings (Vijayalaxmi, 2023). Traditional Swedish underfloor heating systems have typically

operated with inlet water temperatures well below 80 °C. In contrast, modern systems generally utilise inlet water temperatures of around 55 °C, reflecting advancements in design and a focus on improved energy efficiency (Tol and Madessa, 2024).

Currently, more than 50 % of newly built homes in Europe feature underfloor heating as the primary heating method (Ghahramani et al., 2020). This trend has also seen growing adoption in North America. Underfloor heating is especially valued for its ability to create a more consistent and comfortable environment through radiant heat, which is widely appreciated in cultures where sitting and sleeping on the floor is common, such as in many Eastern countries.

Recent research further substantiates the benefits of advanced low-temperature and underfloor heating systems in promoting energy efficiency and occupant comfort. Lund et al. (2014) provide a comprehensive review of modern district heating systems, demonstrating how low-temperature heat distribution networks can be integrated with renewable energy sources to achieve significant efficiency gains (Lund et al., 2014). The International Energy Agency (IEA, 2022) also emphasises the critical role of building energy efficiency measures in mitigating climate change, noting that innovations in heating system design are central to reducing overall energy consumption in both residential and commercial sectors (IEA, 2022). Hesarakı et al. (2015) utilised detailed computational fluid dynamics simulations to compare the thermal performance of underfloor heating systems with traditional radiator systems, confirming that UFH systems achieve a more uniform temperature distribution and reduce thermal stratification under varied conditions (Hesarakı et al., 2015). These additional studies collectively reinforce the view that integrating modern heating technologies with robust control mechanisms and renewable energy sources represents a promising pathway toward sustainable building design.

Although previous studies have emphasised the benefits of low-temperature heating systems – especially underfloor heating – in enhancing energy efficiency and reducing temperature stratification, most research has focused on overall energy consumption or performance in colder climates. A detailed analysis of how room height influences heat distribution and subsequent occupant comfort remains underexplored. This study addresses that gap by numerically simulating temperature gradients across various ceiling heights (2.7 m, 3.0 m, and 3.3 m) under both radiator-based and underfloor heating systems. By investigating the interplay between room height and heat transfer efficiency, the research not only fills an important gap in comparative studies but also provides critical insights for optimising heating strategies

in sustainable building design, thereby improving both energy conservation and occupant comfort in diverse architectural settings.

Methods

This study utilised Computational Fluid Dynamics (CFD) simulations to model temperature distribution in a room heated by two different systems: conventional radiator heating and underfloor heating (UFH). The room dimensions modelled were 3 m × 3 m in width and depth, with ceiling heights of 2.7 m, 3.0 m, and 3.3 m.

Simulation Setup

The simulations were conducted using Fluent software, with the mesh generated in Gambit. Four distinct mesh densities were tested for independence, and the optimal mesh was selected based on the minimal discrepancy between test cases (as shown in Table 1).

Boundary Conditions:

- **Room dimensions:** 3 m × 3 m × 4 m (width × depth × height).
- **Heater dimensions:** 1 m × 0.8 m × 0.5 m.
- **Ceiling heights simulated:** 2.7 m, 3 m, and 3.3 m.
- **Heating system conditions:**
 - Radiator heating was modelled as a heat flux boundary with a constant output of 2kW.
 - Underfloor heating utilised a uniform heat distribution across the floor surface.
 - Ambient temperature: 280 Kelvin (7 °C).
 - Heat transfer coefficient for the walls: $h = 10 \text{ W/m}^2$.
 - Wall thickness: 20 cm, with a thermal conductivity of $K = 1 \text{ W/mK}$ (brick material).

Turbulence was modelled using the RNG k- ϵ equation, accounting for buoyancy effects. Density changes due to temperature differences were modelled using the ideal gas law, given that temperature differentials in the simulations exceeded 20 °C.

Input Parameters:

- **Air properties:** modelled as an ideal gas.
- **Simulation assumptions:** fully turbulent flow, negligible molecular viscosity, heat transfer dominated by convection and radiation.

Results

Verification

For validation purposes, our simulation results were compared with established numerical benchmarks reported in recent CFD studies on thermal engineering, rather than with experimental measurements from studies such as Pereira et al. (2009), which do not provide temperature data for the same room configuration. Specifically, our numerical temperature distributions were evaluated against published data from Iranzo (2019) and Haslinger et al. (2021), both of which emphasise the importance of robust validation techniques in CFD applications (Iranzo, 2019; d'Adamo et al., 2021). Although these references do not offer direct experimental data for our specific room geometry, their reported geometrical specifications and boundary conditions served as reliable benchmarks for our simulation setup. Our analysis indicates that the maximum deviation between our simulated temperature profiles and those reported in the literature is within 5 %, thereby confirming the accuracy of our CFD model. This validation demonstrates the effectiveness of our approach in predicting heat transfer performance across different room heights, and it lays the groundwork for future studies that will incorporate additional comparative parameters, such as heat flux and air velocity measurements, to further refine the model's reliability.

To further enhance the robustness of our validation, future studies will incorporate additional comparative parameters, such as heat flux measurements and air velocity profiles. Including these factors will provide a more comprehensive evaluation of the simulation model, ensuring that it accurately captures the complex interactions governing heat transfer and fluid flow in indoor environments. Such thorough validation is essential for developing reliable models that can inform energy-efficient building designs and effective climate control strategies.

Based on the figure depicted below (Fig. 1), it is observed that the maximum deviation of the graph from the data obtained from the paper's chart is within a margin of 5 %. Consequently, the simulation

Table 1. Average surface temperatures and mesh details for different faces (Source: Authors)

Mesh No.	Mesh Row	Face 1 Temperature (°C)	Face 2 Temperature (°C)	Face 3 Temperature (°C)	Face 4 Temperature (°C)	Face 5 Temperature (°C)
466,253	1	306.3	316.4	330.6	314.2	310.1
864,235	2	309.4	319.3	338.8	318.5	312.3
1,023,268	3	310.6	321.4	339.1	319.3	313.5
15,846,213	4	310.4	321.7	339.4	319.8	313.3

Notes:

- **Mesh No.:** Total number of elements in the mesh.
- **Mesh Row:** Identifier for the mesh configuration.
- **Face 1-5 Temperatures:** Average surface temperatures of the respective faces, in degrees Celsius (°C).

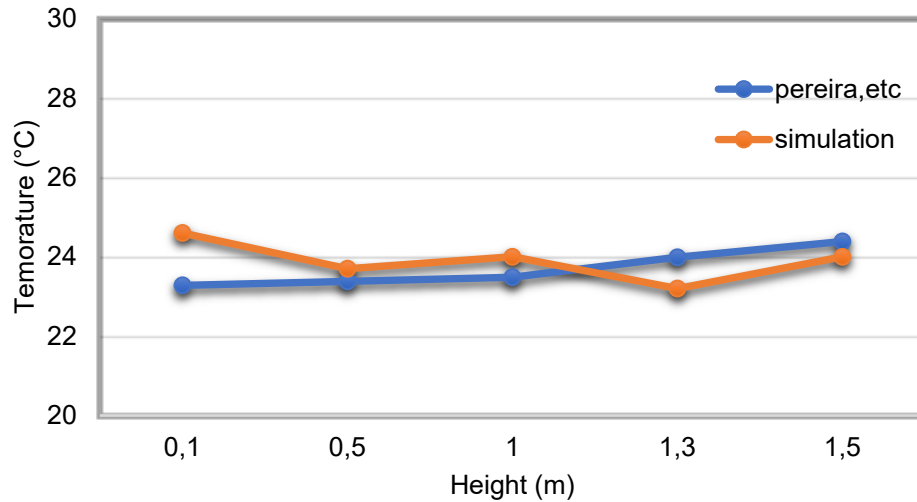


Fig. 1. Simulation verification chart (Source: Authors)

results aligned with those reported in the article are deemed to be satisfactory and reliable.

Determining the Boundary Conditions of the Problem

At this juncture, it is essential to define the boundary conditions for the different sections in our Fluent simulation. These conditions govern parameters such as velocity, fluid pressure, and heat transfer processes on the model's walls. In our study, all boundaries are defined as walls and are grouped into three distinct categories:

1. Heater Boundary Condition (Warm Surface):

The heater is modelled as a wall with a constant heat flux. For an average heater operating at approximately 2 kW, a uniform heat flux of **2000 W** is applied across the heater surface.

2. Floor Boundary Condition (Insulated Surface):

The floor is treated as an insulating boundary where no heat transfer occurs. This is implemented by setting the heat flux to $q = 0 \text{ W/m}^2$.

3. Wall and Ceiling Boundary Condition (Natural Convection):

The surrounding walls and ceiling are modelled with a natural convection boundary condition. A convective heat transfer coefficient of $h = 10 \text{ W/m}^2\text{K}$ is used. External walls are exposed to an ambient temperature of $T_{(\infty)} = 280 \text{ K}$ (approximately 7°C), representing heat loss to the outside air. For simplicity, although the natural heat transfer rate can vary (typically ranging from 5°C to 25°C depending on conditions), a constant value is assumed uniformly across these surfaces. The walls are assumed to be 20 cm thick, constructed of brick with a thermal conductivity of $K = 1 \text{ W/mK}$.

In addition to these boundary conditions, density variations due to temperature fluctuations are modelled using the ideal gas assumption. For buoyancy-driven flow, if the temperature difference

between a wall and the ambient fluid is less than 20°C , the standard buoyancy equation is applied. For larger temperature differentials (exceeding 20°C), the ideal gas assumption is used to avoid significant errors. The simulation also employs the $k-\epsilon$ RNG turbulence model — with pressure and temperature corrections as well as buoyancy effects — to accurately capture turbulence and thermal stratification.

The final boundary conditions set in our simulation are as follows:

- **Heater:** Constant heat flux of 2000 W applied uniformly.
- **Room Walls and Ceiling:** Natural convection with $h = 10 \text{ W/m}^2\text{K}$ and exposure to an ambient temperature of 280 K.
- **Floor:** Insulated with zero heat flux ($q = 0 \text{ W/m}^2$).
- **Material Properties:** Room walls are modelled as brick with a thermal conductivity $K = 1 \text{ W/mK}$.

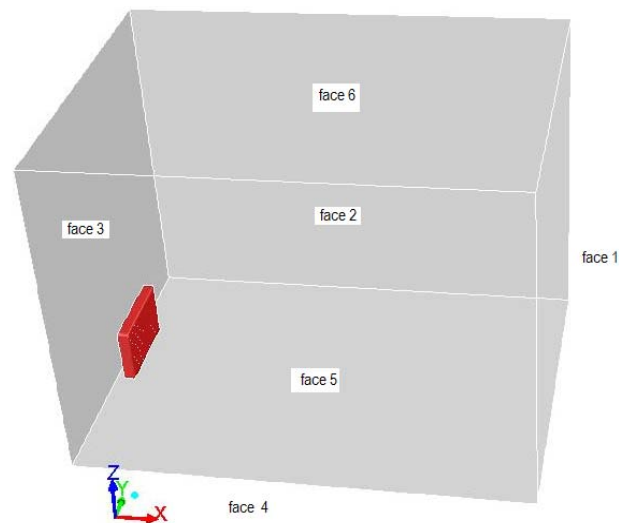


Fig. 2. A view of the simulated room (Source: Authors)

All temperature values in the simulation outputs are reported in degrees Celsius (°C), and unit symbols (W , m^2K , K , etc.) have been verified for consistency (Fig. 2).

Governing Equations

The motion of an incompressible fluid in a turbulent state is described by the Reynolds-averaged Navier–Stokes equations (RANS). These equations consist of the continuity equation, representing mass conservation, and the momentum equation, accounting for the conservation of momentum. The continuity equation is formulated as follows (1):

$$\frac{\partial u_i}{\partial x_i} = 0 \quad i = 1, 2, 3.$$

The momentum equation is:

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + g_i + \frac{\partial}{\partial x_j}(\tau_{ij}) \quad i = 1, 2, 3. \quad (1)$$

In the provided equations, u_i represents the velocity component in the direction x_i , P denotes the total pressure, ρ signifies the fluid density, g_i denotes the acceleration due to gravity in the x_i direction, and τ_{ij} symbolises the stress tensor expressed in the turbulent flow regime, as depicted by the following Equation (2):

$$\tau_{ij} = \left[p(v + v_t) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] - \left[\frac{2}{3} p(l + v_t) \frac{\partial u_i}{\partial x_i} \delta_{ij} \right] \quad i = 1, 2, 3. \quad (2)$$

In turbulent flows, shear stress comprises two components. In addition to the shear stress induced by the mean flow component, there exists another shear stress arising from the fluctuating components of velocity, referred to as the Reynolds stresses. This phenomenon is depicted by Equation (3):

$$\tau_{ij} = -\overline{p u'_i u'_j} = p v_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} p k \delta_{ij} \quad i = 1, 2, 3. \quad (3)$$

The kinetic energy of turbulence on the mass unit (k) is expressed as follows (4):

$$k = \frac{1}{2} \left(\overline{u'^2} + \overline{u'^2} + \overline{u'^2} \right) \quad \delta_{ij} = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}. \quad (4)$$

The turbulence model is essential for resolving turbulent flow fields based on continuity equations and the Reynolds-averaged Navier-Stokes equations. In this context, within the three-dimensional flow regime, comprising four equations (one continuity equation and three momentum equations), the four unknowns of the flow field — namely velocities in the x , y , and z directions, and pressure — are determined.

Turbulence models are employed to characterise Reynolds stresses, thereby facilitating closure of the system of equations. One commonly employed model is the standard k – ε two-equation model. This model, a semi-empirical method, derives the k equation precisely from the governing equations of Reynolds-averaged flow. Conversely, the governing equation for ε is based on empirical and experimental evidence, as well as mathematical relations. During the derivation of the k and ε equations, it is assumed that the flow is fully turbulent, with the influence of molecular viscosity considered negligible. The equations governing this model are expressed by the following relationships (5, 6):

Equation K:

$$\rho \frac{Dk}{Dt} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G_k + G_b - \rho \varepsilon. \quad (5)$$

Equation ε :

$$\rho \frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k - G_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k}. \quad (6)$$

The vortex viscosity is determined in the above equations by the following Equation (7):

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}. \quad (7)$$

The constants of the above equations are in accordance with Table 2.

δ_k & δ_ε are known as the perturbation numbers of Prandtl.

$C_{3\varepsilon}$ is a constant number in ε equation that expresses the effect of velocity in the direction of gravity and perpendicular to it (8).

$$C_{3\varepsilon} = \tanh \left| \frac{v}{u} \right|. \quad (8)$$

Hence, when the flow direction aligns with the gravitational direction, the value of the shear layer in this equation equals 1, whereas if the flow direction is perpendicular to the gravitational direction, this value becomes zero. In the provided equations, G_b represents a term in the k equation that accounts for the buoyancy effect, as expressed in the following Equation (9):

$$Gk = -\rho \overline{u'_i u'_j} \frac{\partial u_j}{\partial x_i}. \quad (9)$$

The floating effect observed by the term G_b is effective when there is a constant temperature and gravity in the problem (10).

$$Gb = \beta g_i \frac{\mu_t}{Pr_t} \frac{\partial T}{\partial x_i}. \quad (10)$$

Table 2. Fixed coefficients for standard equations (Source: Authors)

C_μ	$C_{1\varepsilon}$	$C_{2\varepsilon}$	δ_k	δ_ε
0.09	1.44	1.92	1.00	1.30

Investigating the Contours Related to Simulation

In this section, we present a series of snapshots taken at different time instants during the heating process, illustrating the evolution of velocity vectors and temperature contours within the room. It is important to clarify that the figures do not represent distinct spatial sections of the room, but rather show the transient behaviour of the system over time. In our context, the term “fluid” refers to the air within the room. As the air is heated by the heater, its density decreases, causing it to rise (buoyancy-driven flow), while cooler air descends to replace it.

Figure 3 shows velocity vectors captured at six different time instants during the heating process.

These snapshots illustrate the temporal evolution of the airflow within the room.

Figure 4 presents temperature contours obtained at five different time instants, displayed in various vertical orientations. These contours show that as the heated air rises, the temperature increases from the bottom of the room upward.

Figure 5 demonstrates additional temperature contour snapshots that further detail the progression of the temperature field over time.

Figure 6 depicts density distribution at different time instants, highlighting how the reduced density of heated air drives the upward flow.

Figure 7 displays more velocity vector snapshots, providing further insight into the dynamic behaviour of the air movement over time.

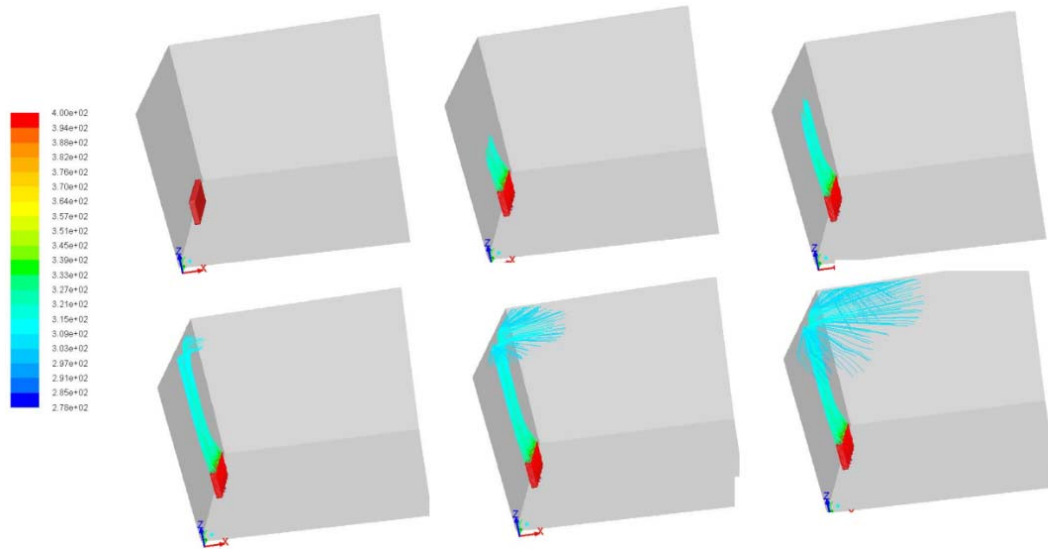


Fig. 3. Speed vector in 6 different sections of the room (Source: Authors)

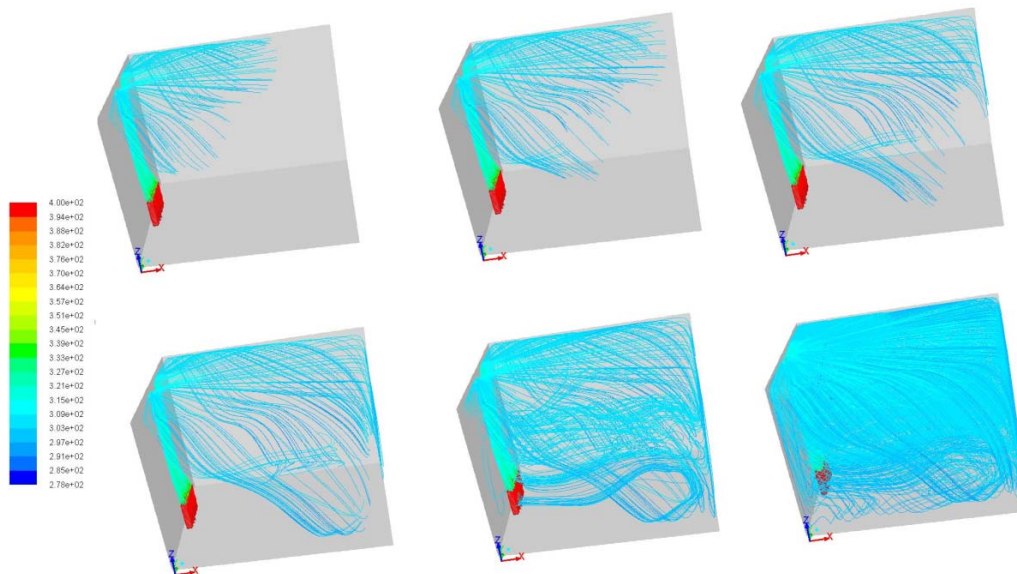


Fig. 4. Temperature contour in 5 different sections in different vertical directions (Source: Authors)

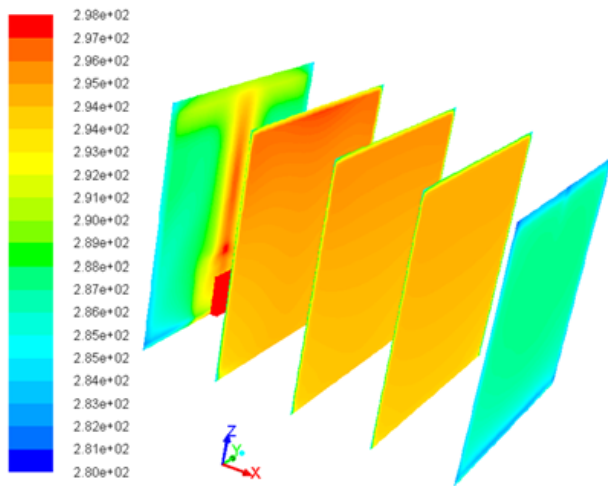


Fig. 5. Temperature contour in 5 different sections of the room
(Source: Authors)

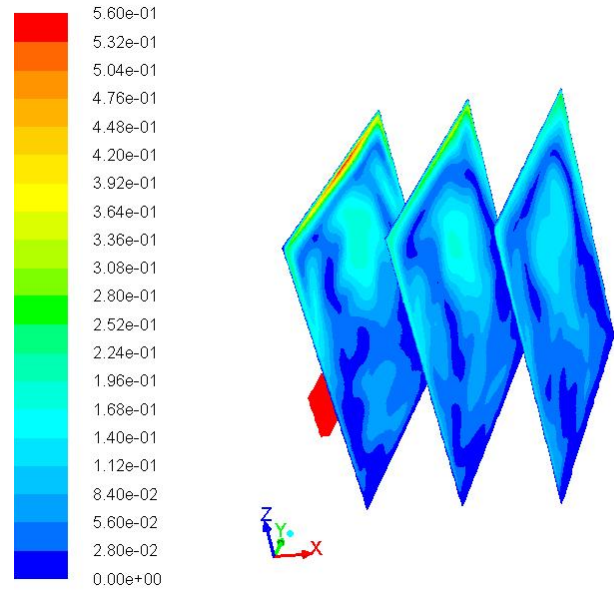


Fig. 8. Speed contour in 5 different sections (Source: Authors)

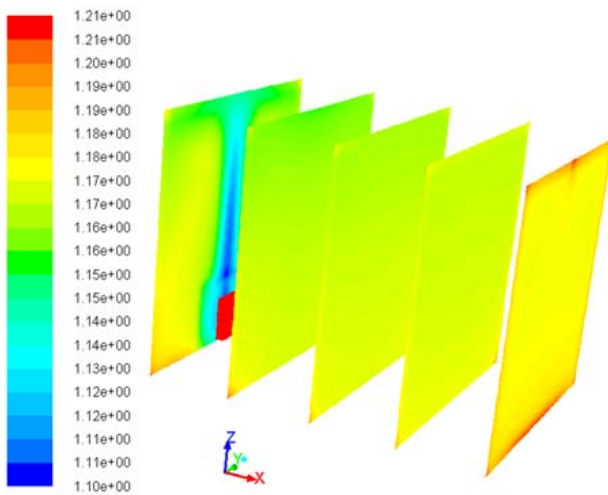


Fig. 6. Density distribution in five different modes (Source: Authors)

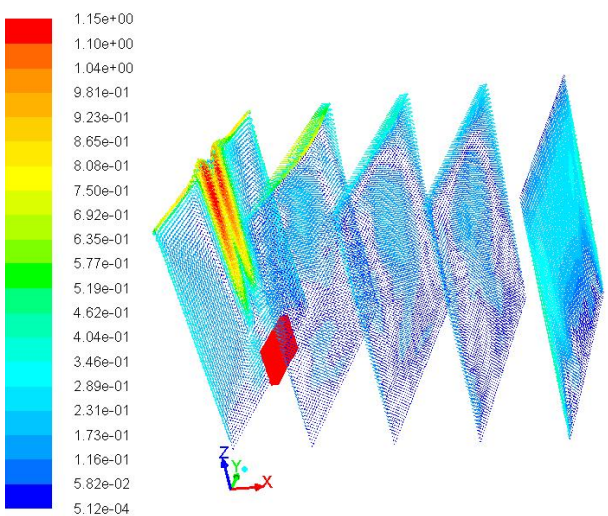


Fig. 7. Velocity vectors in 5 different sections of the room
(Source: Authors)

Figure 8 illustrates speed contours that quantitatively depict the magnitude of air velocity at various time instants.

The results summarised in Table 3 compare the average surface temperatures at the room faces for different ceiling heights. The updated figures now clearly demonstrate the temporal evolution of the system rather than static, separate sections. This approach allows us to analyse how the air (fluid) responds over time to the heating process.

As shown in the figures, as the heated air ascends, it creates a vertical temperature gradient that evolves over time. This buoyancy-driven movement is essential for understanding how ceiling height influences the overall thermal stratification and, consequently, the thermal comfort within the room. For example, while a room with a 2.7 m ceiling may exhibit higher localised temperatures near occupants due to reduced stratification, a 3.3 m ceiling tends to foster a more uniform temperature distribution across the room (Vijayalaxmi, 2023; Cui, 2024).

Furthermore, to enhance our analysis, we provide average room temperature values and standard deviations, which offer a quantitative measure of the heat distribution uniformity. Figs. 9 and 10 further illustrate these findings by comparing temperature contours across different ceiling heights and contrasting the performance of radiator versus underfloor heating systems. This comprehensive evaluation underscores that underfloor heating achieves superior thermal uniformity, thereby optimising energy efficiency and occupant comfort (Ghahramani et al., 2020).

Discussion and Conclusion

The results of this study offer several significant insights into how room height influences thermal

Table 3. Average surface temperatures at room faces (°C) and corresponding ceiling heights (m)
 (Source: Authors)

Face 5 Temperature (°C)	Face 4 Temperature (°C)	Face 3 Temperature (°C)	Face 2 Temperature (°C)	Face 1 Temperature (°C)	Ceiling Height (m)
329	335	348	345	311.1	2.7
313.5	319.3	339.1	321.4	310.6	3.0
307	315	332	318	301	3.3

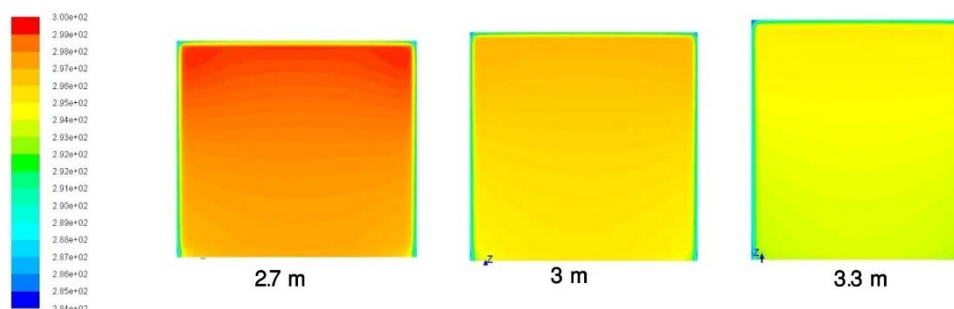


Fig. 9. Distribution of heat in rooms with different ceiling heights (Source: Authors)

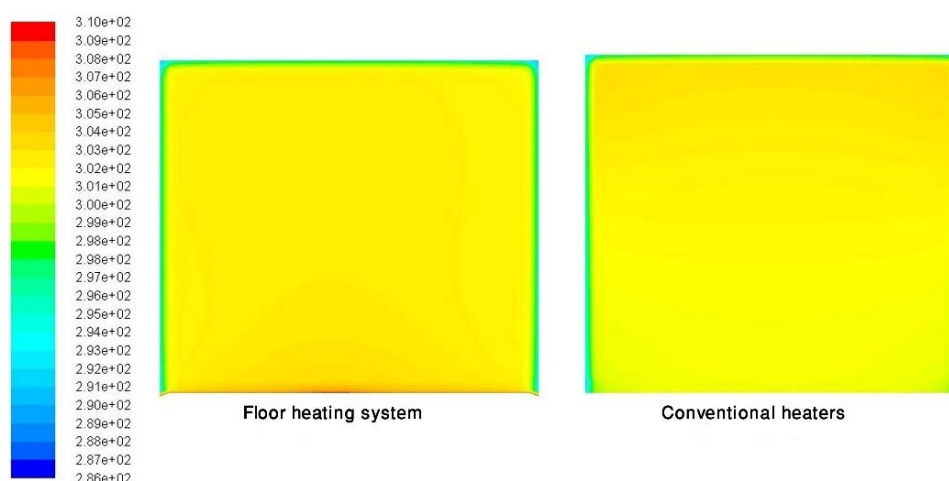


Fig. 10. Distribution of heat with two different heating modes (Source: Authors)

comfort and energy efficiency in buildings using both underfloor heating (UFH) and radiator-based heating systems. To enable a direct comparison, separate CFD simulations were performed for each heating method under identical room conditions and for three distinct ceiling heights (2.7 m, 3.0 m, and 3.3 m). The analysis shows that radiator heating tends to produce significant vertical temperature stratification — particularly in rooms with lower ceilings — where warm air accumulates near the ceiling while cooler air remains near the floor. In contrast, the UFH simulations reveal that underfloor heating delivers a more consistent temperature distribution throughout the occupied zone, effectively reducing the vertical temperature gradient.

Specifically, the simulation data indicate that although a 2.7 m ceiling may yield higher localised

temperatures near occupants for both systems, the overall temperature distribution is markedly more uniform in rooms with a 3.3 m ceiling when using UFH. This is primarily because UFH systems heat the lower part of the room directly, causing a gentle upward flow of air that minimises the pronounced stratification observed with radiator systems. With radiator heating, the convective movement of air tends to create distinct layers: cooler air remains at the lower levels while heated air rapidly rises and accumulates near the ceiling, leading to uneven heating and potential discomfort for occupants. Furthermore, by directly comparing CFD simulation results for both heating systems, our study demonstrates that UFH systems, when integrated with modern low-temperature heat pumps, not only provide superior thermal uniformity but also enhance energy efficiency. The UFH system's ability to

operate at lower water temperatures, typically around 55 °C, reduces energy consumption relative to conventional radiators that require higher operating temperatures. This characteristic makes UFH systems more compatible with renewable energy sources — such as solar thermal or geothermal systems — further contributing to the sustainability of building operations.

The comprehensive analysis includes time-dependent contour plots, velocity vectors, and density distributions, which collectively illustrate the dynamic behaviour of air (the fluid) under both heating scenarios. These detailed visualisations confirm that the interaction between room height and heating system type is a critical factor in achieving optimal thermal performance. For instance, while a room with a 2.7 m ceiling shows higher average temperatures near the floor, the increased stratification in radiator-heated environments can lead to discomfort and inefficient energy use. Conversely, in a 3.3 m room, the UFH system fosters a more gradual temperature increase from floor to ceiling, leading to a balanced indoor environment that enhances occupant comfort.

This study's findings have broad implications for architects and engineers tasked with designing energy-efficient buildings. By demonstrating that the effectiveness of a heating system is not solely dependent on the system's inherent properties but also on the architectural configuration — specifically, room height — our research emphasises the need for integrated design approaches. Such approaches consider both the physical dimensions of a space and the type of heating technology to optimise energy consumption and ensure consistent thermal comfort.

The comparative numerical results presented in this study indicate that underfloor heating (UFH) is likely to produce more uniform temperature

distributions than conventional radiator systems across the ceiling heights considered; however, these findings must be regarded as provisional predictions rather than definitive conclusions. Numerical modelling provides valuable insight into expected behaviours and sensitivities, but real-world applicability can only be established through systematic experimental verification and uncertainty assessment. To address this, we plan to undertake an experimental validation programme that will: (a) reproduce the CFD boundary conditions in instrumented test rooms (or a controlled climatic chamber); (b) acquire steady-state and transient measurements using vertical thermocouple arrays, surface thermistors / IR thermography, local velocity probes, and heat-flux sensors; and (c) compare model outputs with measurements using standard statistical metrics (e.g., mean bias, RMSE) together with uncertainty quantification and sensitivity analysis. If full-scale testing is not immediately feasible, we will begin with scaled laboratory tests and a verification hierarchy (canonical → realistic geometry) to progressively build confidence in the models. We also recommend that future work extend validation to additional variables that influence indoor thermal performance — occupancy patterns, varied construction materials, ventilation / supplemental systems (e.g., ceiling fans), and different control strategies — so that the combined modelling and experimental approach can inform robust, evidence-based design recommendations. By explicitly pairing CFD predictions with a planned programme of targeted experiments, we aim to move from plausible numerical hypotheses to validated knowledge that can reliably guide architects, engineers, and policymakers in selecting heating solutions that balance comfort and energy efficiency.

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ВЛИЯНИЕ ВЫСОТЫ ПОМЕЩЕНИЯ НА ЭФФЕКТИВНОСТЬ ТЕПЛОПЕРЕДАЧИ В РАЗЛИЧНЫХ СИСТЕМАХ ОТОПЛЕНИЯ: ЧИСЛЕННЫЙ АНАЛИЗ

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Цель исследования: настоящее исследование посвящено изучению влияния различной высоты помещений на эффективность теплопередачи систем отопления, с особым акцентом на сравнении традиционного радиаторного отопления и системы напольного отопления. **Методы.** При помощи вычислительной гидродинамики (CFD) были проанализированы распределения температуры при трёх значениях высоты потолка: 2,7 м, 3,0 м и 3,3 м. Численная модель использовалась для исследования характера воздушных потоков, тепловой стратификации и изменения температуры в зоне пребывания людей при различных условиях отопления. **Результаты** показывают, что меньшая высота помещения способствует снижению вертикальной температурной стратификации и, следовательно, повышению общего воспринимаемого уровня температуры, тогда как в более высоких помещениях наблюдаются более выраженные температурные градиенты между полом и потолком. Моделирование также показало, что расположение источника тепла и способ подачи тепловой энергии оказывают существенное влияние на распределение температуры внутри помещения. Кроме того, системы напольного отопления продемонстрировали более высокую тепловую равномерность и энергоэффективность по сравнению с радиаторными системами благодаря более равномерному распределению тепла в нижней, занятой людьми зоне помещения. **Выводы.** Полученные результаты могут способствовать оптимизации энергоэффективности и теплового комфорта пользователей зданий посредством адаптации стратегий отопления к конкретным геометрическим параметрам помещений. Исследование также подчёркивает необходимость учитывать геометрию помещения наряду с выбором системы отопления при оценке тепловых характеристик внутренней среды и разработке энергоэффективных решений для закрытых помещений.

Ключевые слова: подогрев пола, теплопередача, естественное вытеснение, вычислительная гидродинамика.

GEOTECHNICAL ASSESSMENT AND SUSTAINABLE ENGINEERING SOLUTIONS FOR LANDSLIDE MITIGATION AT BAU TRANG LAKE, LAM DONG, VIETNAM

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Abstract

Introduction. This study assesses the landslide and proposes appropriate measures to safeguard the lake system along the Bau Trang shoreline, a well-known ecotourism destination in Binh Thuan province (now part of Lam Dong province), Vietnam. The area is threatened by shoreline landslips caused by both natural hazards and human activity. **Methods.** The methodology employed topographic and geomorphological geotechnical techniques, remote sensing, and Geographic Information Systems (GIS), using Geo-studio models. **Results.** The findings indicate that sections of the lakeshore with low safety factors are particularly vulnerable due to the reservoir's fluctuating water level, vibrations, and the movement of cruise ships. To improve lakeshore stability, various technical solutions were proposed, including live load reduction plates, geotechnical textiles, reinforced concrete (RC) sheet piles, Melaleuca (Cajuput) timber piles, and sandbag revetments. These measures are expected to not only ensure the safety of the lakeshore but also protect the ecosystem and environment, supporting the need to preserve this outstanding natural and scenic location.

Keywords: lakeshore erosion; landslide mitigation; geotechnical stability; Geo-studio; Bau Trang lake; sustainable engineering; eco-tourism.

Introduction

Lakeshore environments, particularly those of significant ecological and socio-economic value, are increasingly recognised as fragile ecosystems vulnerable to geomorphological instability (Medeu et al., 2023; Yang et al., 2019). Bau Trang Lake, situated in Hoa Thang Commune, Bac Binh District, Binh Thuan Province (now part of Lam Dong Province), Vietnam, is a prime example of such a vulnerable system. Renowned for its unique landscape featuring striking white sand dunes juxtaposed with diverse aquatic habitats, Bau Trang has been officially designated a National Scenic Landscape by the Vietnamese Ministry of Culture, Sports, and Tourism (Binh Thuan Portal, 2021). This status underscores its immense natural and cultural importance, contributing significantly to regional tourism and local livelihoods, especially following the post-COVID-19 resurgence in visitor numbers.

However, the integrity of Bau Trang Lake is under considerable threat from lakeshore erosion. A particularly severe event occurred on May 3, 2023, along the northeastern shore of Bau Ba, a constituent

part of the Bau Trang lake system. This event resulted in an approximately 80-metre-diameter semi-circular scarp, triggering substantial public and governmental concern regarding the site's stability and long-term preservation (Phap Luat, 2023). Such instabilities not only jeopardise the delicate aquatic ecosystem and the aesthetic appeal crucial for tourism but also pose direct risks to public safety and local infrastructure, potentially undermining the regional economy. The Binh Thuan (now Lam Dong) Provincial People's Committee subsequently initiated urgent investigations to determine the causative factors and formulate remedial strategies (Phap Luat, 2023).

The instability of lakeshores is a complex phenomenon driven by a confluence of natural and anthropogenic factors. Natural drivers prominently include wave action and fluctuations in water levels, which can significantly alter sediment dynamics and induce erosion, as documented in studies of various lake systems globally (Medeu et al., 2023; Davidson-Arnott and Ollerhead, 1995). For instance, rapid reservoir drawdown rates have been shown

to decrease bank stability by increasing pore water pressures and reducing effective stress (Yang et al., 2019). Soil properties and groundwater seepage also play a critical role in determining susceptibility to erosion and mass movement (Hansom and McGlashan, 2000). Furthermore, the escalating impacts of climate change, manifesting as altered hydrological regimes and an increased frequency of extreme weather events, are expected to exacerbate these erosional processes in lacustrine environments (Sun, 2014; Arnaud, 2016). Anthropogenic activities often compound these natural vulnerabilities. Even though protection structures are meant to be remedial, their construction may unintentionally exacerbate erosion nearby (Abrahams, 2008). Increased vehicle traffic along lakeshores can put additional strain on slopes in areas with high tourism intensity, such as Bau Trang, which could lead to collapses. While extensive research has elucidated many of these individual factors, and various modelling approaches, including machine learning techniques, have been developed to predict landslide susceptibility in reservoir environments (Holanda et al., 2021), a holistic understanding of the synergistic interplay between natural processes and intense, localised tourism-related pressures in a designated national heritage site remains a critical area for investigation.

This study aims to address this gap by undertaking a comprehensive assessment of the shoreline transformations and geotechnical stability of Bau Trang Lake. The specific objectives are: (1)

to evaluate the historical and recent evolution of landslides and shoreline changes using integrated field surveys and multi-temporal remote sensing data; (2) to analyse the geotechnical stability of the lakeshore under various natural and anthropogenic loading scenarios using advanced numerical modelling with Geo-studio; and (3) to propose and evaluate environmentally considerate engineering solutions designed to enhance shoreline stability and ensure the long-term protection of this valuable landscape. The findings are anticipated to provide a robust scientific basis for sustainable management strategies at Bau Trang and offer transferable insights for other ecologically sensitive and economically vital lakeshore systems facing similar challenges worldwide.

Materials and Methods

Study Area

This research concentrated on the northeastern shoreline of Bau Ba Lake, a constituent of the larger Bau Trang Lake system in Binh Thuan Province (now part of Lam Dong Province), Vietnam (Fig. 1). This specific area, encompassing the Trinh Nu dune, has been subject to significant recent landslide activity and is characterised by extensive aeolian sand dunes, a diverse but fragile ecosystem, and high sensitivity to both natural geomorphological processes and anthropogenic pressures, particularly from tourism-related activities.

Data Collection

A multi-faceted data collection strategy was employed, integrating field surveys with remote

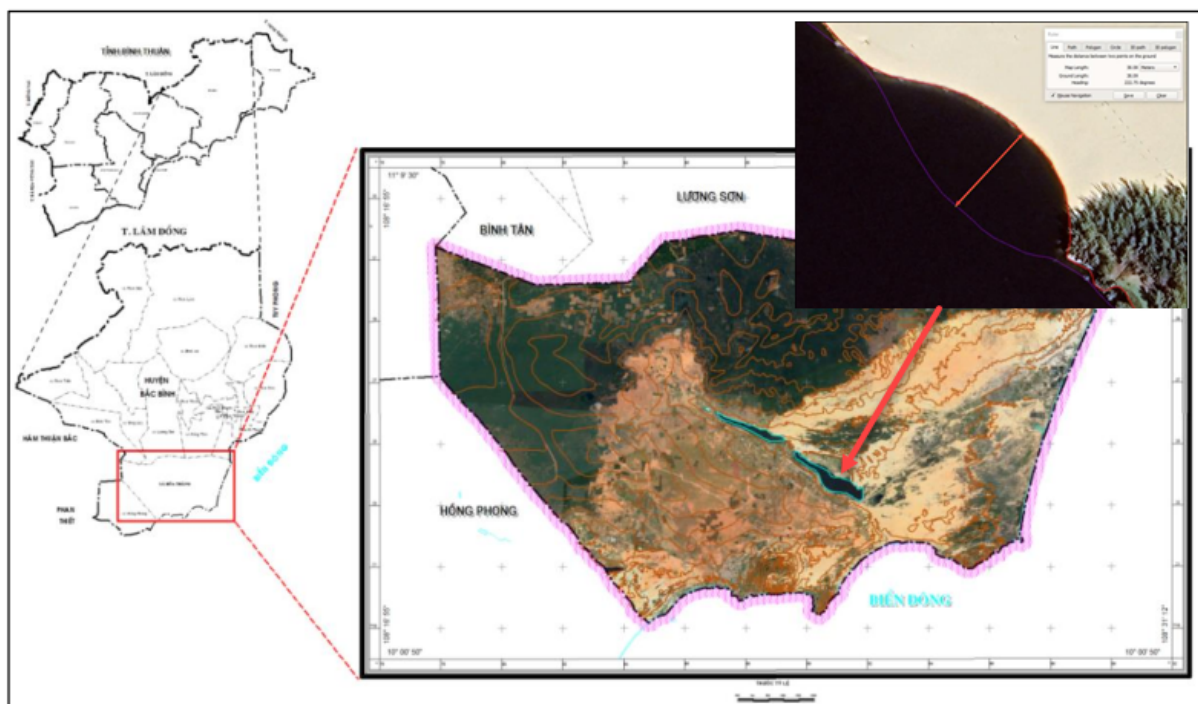


Fig.1. The study area

sensing techniques to provide a comprehensive understanding of the site's conditions and dynamic processes.

a) Field surveys

Direct field investigations were conducted to gather high-resolution data on current landslide geometry, sediment characteristics, and shoreline morphology. These surveys involved:

- detailed measurement of landslide depths and dimensions;
- collection of soil samples for the determination of geotechnical parameters, including sediment composition and physical properties;
- topographic profiling and slope angle measurements along critical sections.

A total of 53 survey points were established along key shoreline segments, selected based on pre-assessment of erosion hotspots and historical data. Repeat surveys of the Trinh Nu dune area were conducted on January 25, 2024; February 25, 2024 and March 25, 2024, to monitor short-term transformations of the dune.

b) Remote sensing and Geographic Information System (GIS) methods

Multi-temporal remote sensing data were utilised to assess long-term topographic changes, shoreline evolution, and sand dune migration patterns. The datasets included:

- Satellite Imagery: A chronological series of satellite images spanning from 1984 to 2022 was acquired. This included moderate-resolution imagery

for historical trend analysis and high-resolution imagery (0.5 m spatial resolution) available from 2006 onwards for more detailed recent assessments (Fig. 2).

- Historical Maps: Cartographic records, including maps from the early 19th century, the French colonial era, the 1950s-1960s (US era), and current VN2000 standard topographic maps, were consulted for historical shoreline positions.

- UAV-derived Digital Elevation Models (DEMs): High-precision DEMs were generated from Unmanned Aerial Vehicle (UAV) surveys to accurately map recent changes in slope, elevation, and landform features.

- Google Earth Timelapse: Imagery from Google Earth Timelapse (1984-2022) was used for a qualitative visual assessment of broad-scale land cover and environmental changes in the Bau Trang area over several decades.

c) Geotechnical modelling

The stability of the lakeshore slopes was analysed using Geo-studio 2021 software (Geo-Slope International Ltd.), a widely recognised suite for geotechnical modelling. The SLOPE/W module, which employs limit equilibrium methods, was specifically used for slope stability analysis.

- Cross-sections: Nine critical cross-sections were selected for detailed analysis (Fig. 7): four within the Bau Ong area (MC5, MC6, MC7, MC9) and five within the Bau Ba area (L1, L4, L8, MC2, MC4), with L1, L4, and L8 directly traversing the recent landslide zone.

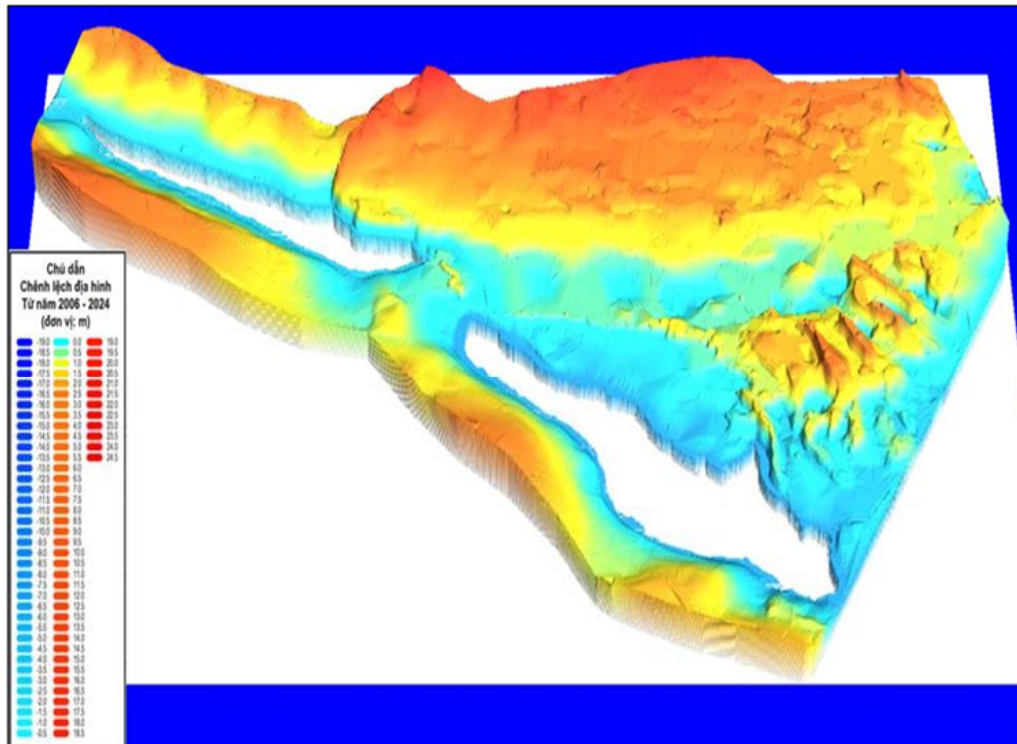


Fig. 2. Three-dimensional model of terrain difference in the Bau Trang lake area (2006–2024)

- **Soil Parameters:** The Mohr-Coulomb failure criterion was adopted for the soil model. Geotechnical parameters, including unit weight (γ), cohesion (c), and angle of internal friction (ϕ) for different soil layers (Table 1), were derived from the field investigations and laboratory testing of collected samples.

- **Analysis Scenarios:** The stability analyses were conducted under various scenarios to evaluate the influence of:

- **Water Level Fluctuations:** different lake water levels were considered for Bau Ba (+32 m, +33 m, +34.2 m mean, +36 m) and Bau Ong (+36 m, +38.6 m, +40 m).

- **Live Loads:** static surcharge from tourist vehicles (2.0 - 2.5 ton pickup trucks and smaller ATVs), applied approximately 3 m from the lake shore, was modelled according to TCVN 2737–2023.

- **Seismic Loads:** dynamic loading due to vibrations from tourist vehicles was incorporated, using a maximum ground acceleration of 14.4 m/s² (equivalent to 0.00147 g), as recorded on February 25, 2024.

- Associated seepage and stress analyses were also performed where relevant.

d) Data analysis and stability assessment criteria

Geographic Information System (GIS) software was employed for processing satellite imagery, analysing DEMs, quantifying spatial changes in shoreline position and topography, and generating cartographic outputs. The stability of the slopes was assessed based on the calculated Factor of Safety (FoS). According to Vietnamese standard TCVN 8216:2018 for hydraulic structures, a minimum FoS of 1.25 is generally required for Class IV earth fill dams under normal operating conditions, a threshold adopted for assessing the stability of the lakeshore slopes in this study.



Fig. 3. Movement of the sand dunes during three surveys of the Trinh Nu hill

Results

a) Topographic and geomorphological changes in the Trinh Nu dune area

Repeated topographic surveys of the Trinh Nu dune area between January and March 2024 revealed significant short-term dynamics. The crest of the Trinh Nu dune exhibited a discernible westward migration towards Bau Ba Lake. Over the three survey periods, the northern part of the dune crest shifted by approximately 5 m, while the southern part moved by approximately 10 m (Fig. 3). Despite this lateral movement, no significant changes in the overall crest elevation range (30–83 m) were observed.

Analysis of DEM difference maps (Fig. 4a and 4b, scale 1:1,000) illustrated these changes more clearly. For the period from January 25 to February 25, 2024, localised areas experienced elevation decreases of up to 2 m, predominantly in the central part of the surveyed dune, interspersed with elongated sand deposits along the dune toe. Concurrently, areas of accretion, with elevation gains of 1 to 4 m, were noted around the periphery of the Trinh Nu dune.

During the subsequent period (from January 25 to March 25, 2024), more pronounced changes occurred, with some areas showing elevation decreases of up to 6 m and more widespread accretion of up to 4 m. A consistent observation was the formation of new, elongated lakeside dunes oriented northwest-southeast along the margin of Bau Ba Lake, characterised by steep slopes ranging from 20° to 55°, which later steepened to 30°–55°. Within a specific 0.48-hectare area identified as highly prone to landslides (Fig. 5), the average ground elevation decreased by 0.52 m over the two-month observation period (from January 25 to March 25, 2024), from an initial average of 37.88 m to 37.36 m.

b) Shoreline transformations of Bau Ba lake (Trinh Nu area)

Analysis of satellite imagery spanning eight distinct time periods between 2006 and 2023 indicated a predominant trend of southwestward migration of the Bau Ba Lake shoreline in the vicinity of the Trinh Nu dune. This migration is attributed to the progressive deposition of aeolian sand transported by the prevailing northeast monsoon winds (Fig. 6). The rate of shoreline change was not uniform; the northern section of the shoreline experienced more

Table 1. Parameters of soil layers

Soil layer	Gama [kN/m ³]	Phi [o]	C [kPa]
1	19.9	24°56	1.4
1a	20.1	25°14	1.9
2	20.3	26°46	1.1
2a	19.9	26°45	1.8
3	20.5	28°56	1.2

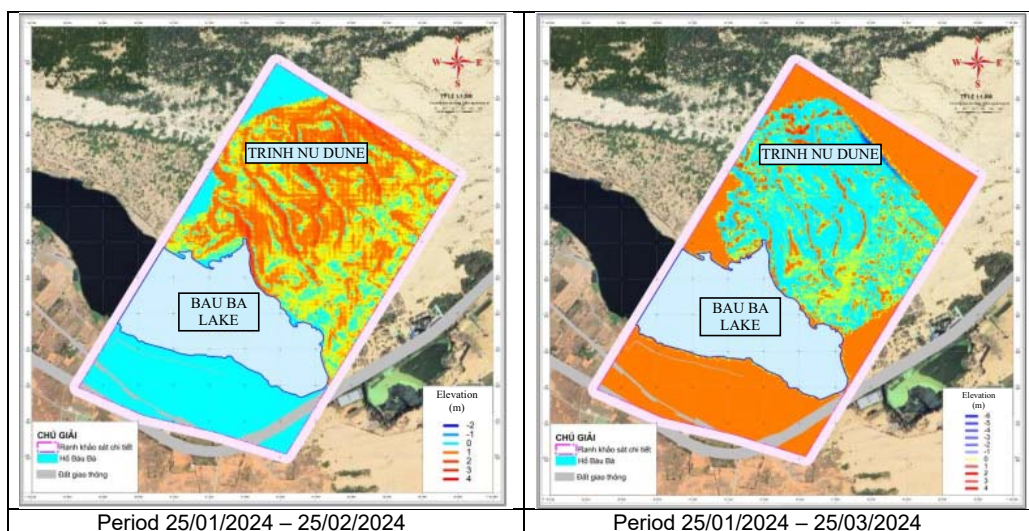


Fig. 4. Map of the Trinh Nu hill area's topographic variations throughout time, scaled at 1:1,000

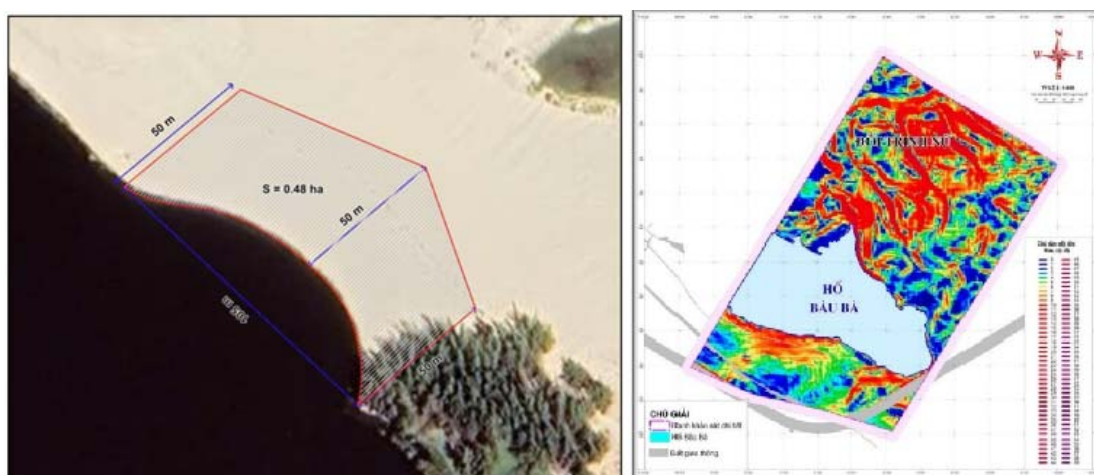


Fig. 5. Variations in the study area's terrain

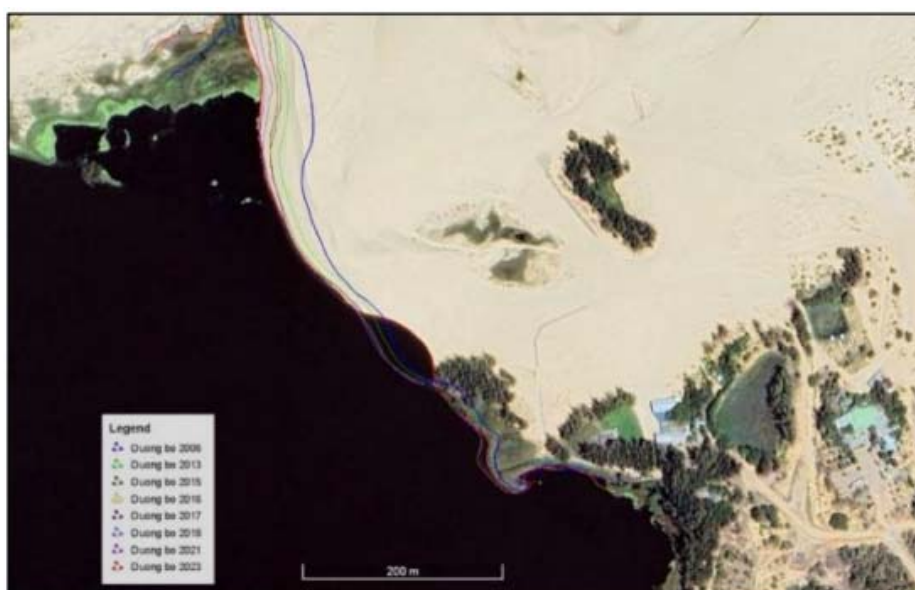


Fig. 6. Shoreline changes over time

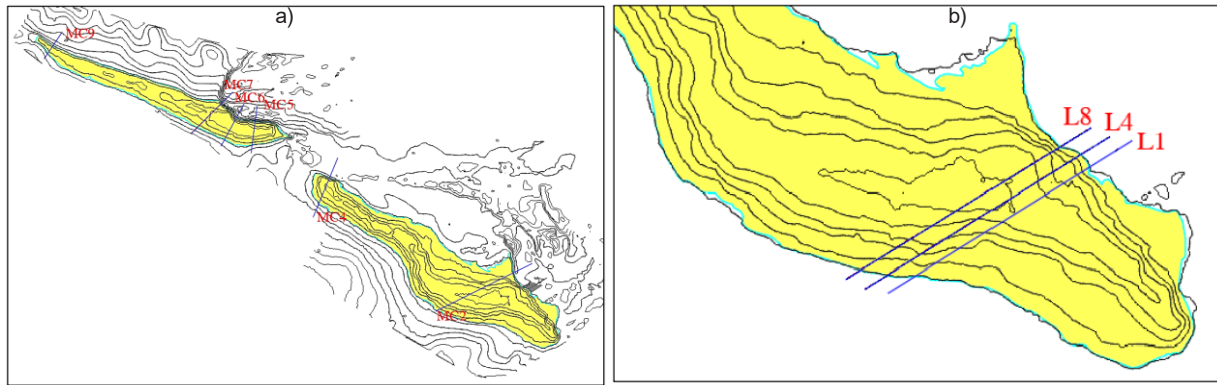


Fig. 7. Shoreline cross-sections: (a) cross-section along the Bau Ong shoreline; (b) cross-section along the Bau Ba shoreline

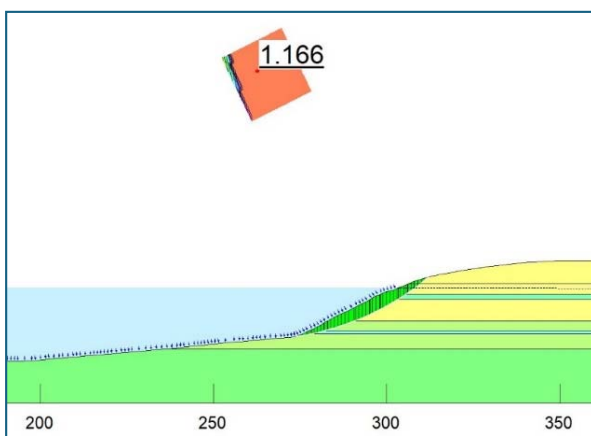


Fig. 8. Results of the calculation model for cross-section L8 at water level +34.2 m

rapid accretion, advancing approximately 50 m (an average of 3 m per year), which is five times greater than the southern section, where accretion was approximately 10 m (an average of 0.6 m per year), excluding the area directly affected by the recent major landslide.

c) Geotechnical stability analysis of the existing shoreline (pre-mitigation)

The geotechnical stability of nine selected cross-sections (Fig. 7) along the Bau Ong and Bau Ba

shorelines was evaluated using Geo-studio SLOPE/W, incorporating the soil parameters detailed in Table 1.

The analyses considered various scenarios of lake water levels and applied loads. Particular attention was given to cross-sections L1, L4, and L8 within the Bau Ba landslide zone. For instance, under a lake water level of +34.2 m and subjected to dynamic loads from tourist vehicles, cross-section L8 exhibited a Factor of Safety (FoS) of 1.166 (Fig. 8). The critical slip surface for this scenario was characterised by a depth of approximately 4 m and a width of about 35 m, extending from an elevation of +36.5 m down to +20.5 m.

The relationship between FoS and lake water level for the Bau Ba sections is presented in Fig. 9, and for the Bau Ong sections in Fig. 10. These results indicated that several cross-sections, notably L8, MC2, and MC4 in Bau Ba, and MC5, MC6, and MC7 in Bau Ong, possessed FoS values below the recommended minimum of 1.25 (TCVN 8216:2018, 2018), signifying a high risk of instability. Cross-sections L4 and L8 were identified as particularly vulnerable, with stability further deteriorating under conditions of reduced lake water levels.

d) Proposed engineering solution for landslide mitigation

Based on the stability analyses and site conditions, an integrated engineering solution was

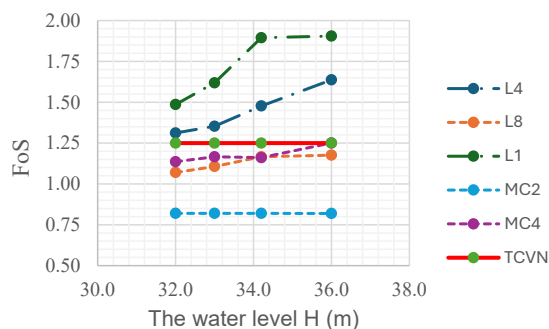


Fig. 9. Stability calculation results for Bau Ba Lake

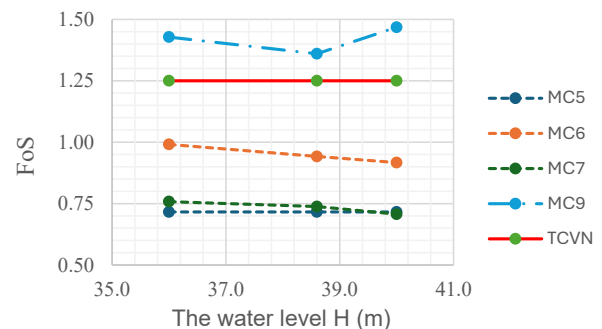


Fig. 10. Stability calculation results for Bau Ong Lake

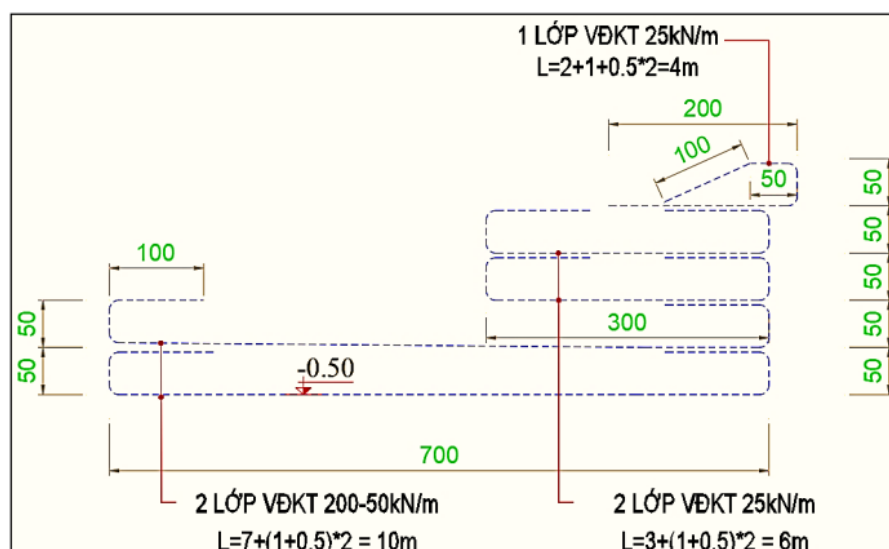


Fig. 11. Geotextile layout details

developed to mitigate landslide risk, particularly for the unstable sections of Bau Ba Lake. The design adhered to principles of heritage conservation, environmental compatibility, and technical efficacy. The proposed solution (detailed for the representative cross-section L8 in Fig. 12) comprises a combination of:

- Reinforced concrete (RC) sheet piles: To be installed from approximately +34.7 m down to +14.7 m elevation to provide deep-seated stabilisation at the interface between the slumped material and the intact ground.
- Melaleuca (Cajuput) timber piles: Driven into the ground for soil reinforcement and support. These piles are specified with an 8–10 cm butt diameter and lengths of 5.5 m and 4.5 m, installed at a density of approximately 8 piles per meter.
- Geotextile layers: Multiple layers of geotextiles with specified tensile strengths (ranging from 25–50 kN/m to 200 kN/m) are incorporated for soil reinforcement, separation, filtration, and load distribution (Fig. 11).
- Sandbag revetment: To provide immediate, temporary protection for the slope toe against wave action during the implementation of more permanent measures.

This combined system is designed for an expected service life of 15–20 years.

e) Stability analysis of the shoreline with proposed solution (post-mitigation)

The stability of the critical cross-section L8 was re-analysed using SLOPE/W after incorporating the proposed engineering solution. The results demonstrated a significant improvement in stability, with the Factor of Safety increasing from the pre-mitigation value of 1.166 to 1.568 (Fig. 13). This indicates that the proposed measures effectively

enhance the stability of the lakeshore to an acceptable level.

Discussion

a) Interpretation of key findings

The observed topographic changes within the Trinh Nu dune area, particularly the westward migration of the dune crest and the formation of new lakeside dunes, are consistent with active aeolian processes driven by the prevailing northeast monsoon. The quantified movement of the dune crest, up to 10 m in its southern part over a short three-month period, highlights the dynamic nature of this landscape and its direct influence on the Bau Ba Lake shoreline through sediment input. The concomitant decrease in average ground elevation within the landslide-prone zone suggests ongoing mass wasting, likely exacerbated by this continuous sediment loading and undercutting at the toe by lake processes.

The long-term shoreline dynamics of Bau Ba Lake confirm the dominant role of wind-driven sediment transport in shaping this environment. The differential accretion rates, with the northern shoreline advancing more rapidly, can be attributed to variations in sediment supply and local exposure to wind action. These geomorphological observations align with studies elsewhere that emphasise the role of aeolian transport in coastal and lacustrine environments (Kirk et al, 2000).

The geotechnical stability analyses revealed that several sections of the Bau Trang lakeshore, particularly L4 and L8 in the Bau Ba area, possess Factors of Safety below the nationally accepted threshold of 1.25 (TCVN 8216:2018, 2018), rendering them susceptible to failure. The low stability is attributed to a combination of factors: the inherent properties of the predominantly sandy soils (low

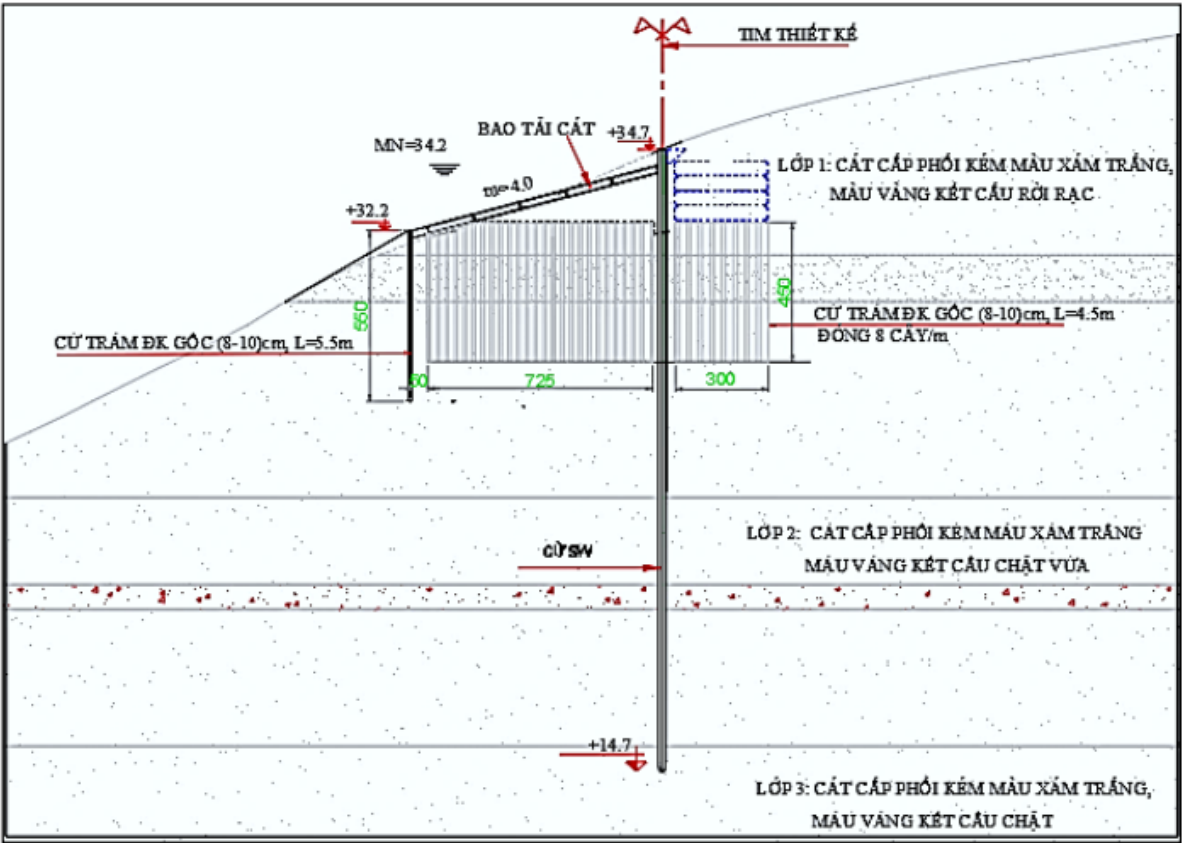


Fig. 12. Landslide prevention design for cross-section L8

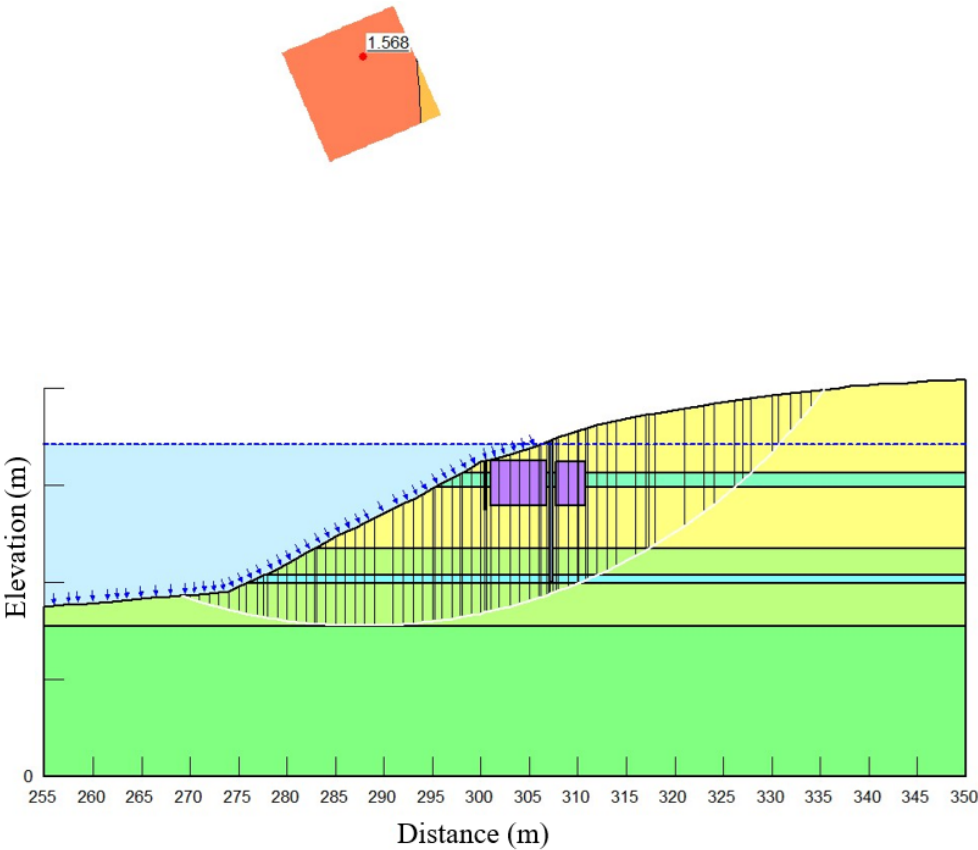


Fig. 13. SLOPE/W analysis results for cross-section L8

cohesion), the destabilising effect of reduced lake water levels which decrease buttressing support at the toe, and the superimposed dynamic loads from tourist vehicles. The identified critical FoS of 1.166 for section L8 under specific loading and water level conditions underscores the precarious state of these slopes and corroborates the observed landslide events. This sensitivity to water level fluctuations and surcharge loading is a well-documented phenomenon in slope stability assessments (Yang et al., 2019).

b) Effectiveness and rationale of proposed engineering solution

The proposed integrated engineering solution, combining RC sheet piles, Melaleuca timber piles, geotextile reinforcement, and sandbag revetment, was designed to address the complex failure mechanisms identified. RC sheet piles offer deep-seated stabilisation by creating a shear-resistant barrier and retaining the potentially unstable soil mass. The use of locally sourced, environmentally compatible Melaleuca piles contributes to internal soil reinforcement and improves drainage, enhancing the overall soil mass properties. Geotextiles play a crucial role in reinforcing the soil, distributing loads, preventing the migration of fine particles (filtration), and separating different soil layers. The sandbag revetment provides immediate, cost-effective toe protection against wave erosion during the construction phase and for short-term defence.

The significant improvement in the Factor of Safety for the critical L8 section, from 1.166 to 1.568 post-mitigation, demonstrates the technical efficacy of this composite solution in enhancing shoreline stability to well above acceptable engineering standards. This approach contrasts with some traditional hard engineering solutions, such as extensive rock revetments, which can be visually intrusive and may negatively impact local sediment dynamics and ecological habitats (Abrahams, 2008; Nakagawa et al., 2013). The chosen solution prioritises environmental sensitivity and aesthetic integration, which are paramount for a national scenic heritage site like Bau Trang.

c) Implications of the study

This research provides a critical scientific basis for immediate intervention and the development of long-term, sustainable shoreline management plans for Bau Trang Lake. The detailed assessment of instability mechanisms and the validated effectiveness of the proposed solution offer actionable insights for local authorities and site managers. Furthermore, the methodological framework, integrating field investigations, remote sensing, and geotechnical modelling, can be adapted for assessing and managing similar ecologically sensitive and economically important tourism destinations facing comparable erosion and landslide risks globally. The emphasis on environmentally considerate

engineering solutions is particularly relevant for protected areas where conservation objectives must be balanced with development needs.

d) Limitations of the study

While this study provides a comprehensive assessment, certain limitations should be acknowledged. The geotechnical parameters used in the modelling, although based on site investigations, may exhibit local spatial variability not fully captured. The direct observations of dune movement, while indicative of active processes, were conducted over a relatively short period (three months) and may not represent longer-term annual or decadal trends. The modelling of dynamic loads from tourist vehicles, while incorporating recorded accelerations, is a simplification of complex vehicle-ground interactions. Furthermore, the long-term ecological response to the implemented engineering solutions will require ongoing monitoring.

e) Recommendations for future research

To build upon this work, several avenues for future research are recommended. Long-term monitoring of the implemented stabilisation measures and continued surveillance of shoreline changes are crucial to evaluate the sustained effectiveness of the solutions and adapt management strategies if necessary. More detailed hydrogeological investigations could elucidate the complex interactions between groundwater levels, lake water levels, and slope stability. Research into the specific ecological impacts of both the landslides and the mitigation measures on the aquatic and terrestrial habitats of Bau Trang would be beneficial. Finally, the development of a holistic, integrated risk management plan for the entire Bau Trang ecosystem, considering all interacting natural and anthropogenic factors, should be a priority.

Conclusion

This study has comprehensively assessed the critical issue of shoreline erosion and landslide susceptibility threatening the ecological integrity and tourism value of Bau Trang Lake, a national scenic heritage site in Vietnam. The investigation revealed that specific sections of the lakeshore, particularly within the Bau Ba area (notably cross-sections L4 and L8), exhibit low Factors of Safety (FoS < 1.25), rendering them unstable under prevailing natural conditions and exacerbated by anthropogenic pressures, including fluctuating lake water levels and dynamic loads from tourism activities. The observed dune migration and shoreline changes further underscore the dynamic and vulnerable nature of this unique lacustrine environment.

An integrated engineering solution, comprising reinforced concrete sheet piles, Melaleuca timber piles, geotextile reinforcement, and sandbag revetments, was proposed and evaluated. Geotechnical modelling demonstrated that this

solution significantly enhances shoreline stability, increasing the Factor of Safety for the critical L8 section from 1.166 to 1.568. This confirms the technical feasibility and effectiveness of the proposed measures in mitigating landslide risk while being designed to be environmentally considerate and to preserve the aesthetic qualities of the site.

The findings provide a robust scientific foundation for immediate and long-term management interventions at Bau Trang Lake.

More broadly, this research offers a valuable methodological framework and a practical example of sustainable engineering applicable to other ecologically sensitive lakeshore environments facing similar geomorphological challenges globally. The study underscores the necessity for prompt implementation of these protective measures by relevant authorities, in collaboration with scientific expertise, to ensure the enduring conservation and sustainable development of the Bau Trang landscape for future generations.

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ГЕОТЕХНИЧЕСКАЯ ОЦЕНКА И УСТОЙЧИВЫЕ ИНЖЕНЕРНЫЕ РЕШЕНИЯ ДЛЯ ПРЕДОТВРАЩЕНИЯ ОПОЛЗНЕЙ НА ОЗЕРЕ БАУ ТРАНГ, ЛАМДОНГ, ВЬЕТНАМ

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Аннотация

Введение. В данном исследовании проводится оценка оползней и предлагаются соответствующие меры по защите озерной системы вдоль береговой линии Бау Транг, известного места экотуризма в провинции Биньтхуан (ныне часть провинции Ламдонг), Вьетнам. Территория находится под угрозой береговых оползней, вызванных как природными катаклизмами, так и деятельностью человека. **Методы.** В исследовании использовались топографические и геоморфологические геотехнические методы, дистанционное зондирование и географические информационные системы (ГИС) с применением моделей Geo-studio. **Результаты** показывают, что участки береговой линии с низким коэффициентом безопасности особенно уязвимы из-за колебаний уровня воды в водохранилище, вибраций и движения круизных судов. Для повышения устойчивости береговой линии были предложены различные технические решения, включая пластины для снижения эксплуатационных нагрузок, геотехнические текстильные материалы, железобетонные шпунтовые сваи, сваи из древесины мелалеуки (каяпута) и укрепления из мешков с песком. Ожидается, что эти меры не только обеспечат безопасность береговой линии, но и защитят экосистему и окружающую среду ради сохранения этого выдающегося природного и живописного места.

Ключевые слова: эрозия береговой линии; предотвращение оползней; геотехническая устойчивость; Geo-studio; озеро Бау Транг; устойчивое строительство; экотуризм.

A CRITICAL REVIEW OF THE INFLUENCE OF PARTICLE MORPHOLOGY AND POROSITY ON SOIL THERMAL CONDUCTIVITY

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Abstract

Introduction. This critical review underscores the importance of examining key factors such as particle morphology and porosity in the extensive body of literature on soil studies. A deeper understanding of how these elements influence soil thermal conductivity is essential for advancing knowledge in geotechnical and environmental research. **Methods.** By synthesising findings from a wide range of studies, this review highlights the complex nature of soil thermal conductivity and stresses the need to thoroughly investigate these parameters. Each factor plays a crucial role in determining heat transfer behaviour in soils. Through an in-depth analysis of existing research, this paper emphasises the necessity of systematically studying these variables to resolve inconsistencies, fill knowledge gaps, and enhance predictive models for geotechnical and environmental applications. **Conclusions.** Recently developed multi-variable functions offer a robust framework for predicting soil thermal conductivity by integrating these influential parameters. By providing a comprehensive perspective that connects theory with practical application, this review serves as a vital resource, supporting both scientific exploration and engineering practice.

Keywords: thermal conductivity, granular soils, factors, critical review, proposed models.

Introduction

Thermal conductivity is a crucial physical characteristic of soils that gauges their heat conduction capacity. It represents the rate at which heat traverses a unit area under a unit temperature gradient — essentially the quantity of heat passing through soil per unit area and time, divided by the temperature difference across the soil layer (Zhang et al., 2017; Kashani et al., 2017). The thermal conductivity of soils, particularly sands, has long captivated researchers and engineers due to its significance in geotechnical and environmental engineering applications. Understanding its origin and historical aspects is imperative for accurate behaviour prediction (Yun and Santamarina, 2008; Chen et al., 2014; Liu et al., 2020). Thermal conductivity serves as a crucial parameter for understanding soil thermal characteristics and environmental interactions. It plays indispensable roles in geothermal energy, building energy efficiency, and underground construction. Research efforts have focused on understanding influencing factors and developing precise predictive models across various soil types and conditions (Johansen, 1977; Lu et al., 2007; Zhang et al., 2015). Studies have also explored the influence of soil texture and mineralogy (Barry-Macaulay et al., 2013). Accurate measurement is essential for geothermal energy, building efficiency, and underground construction applications (Adam and Markiewicz, 2009; Loveridge and Powrie, 2013; Wang et al., 2016). Influential factors on granular soil

thermal conductivity include particle shape and size, porosity, rubber content, soil composition, moisture content, soil type, temperature, compaction, packing density, saturation, freeze-thaw cycles, polymers, and bio-cementation methods. Each factor significantly impacts thermal conductivity, requiring detailed study. Fig. 1 incorporates these influential parameters, with their soil impacts depicted in Fig. 2.

Literature Review

The literature on soil thermal conductivity contains apparent contradictions due to varying research perspectives. Numerous researchers have examined the thermal characteristics of sand, silt, and clay soils (Cai et al., 2015; Zhang et al., 2017). Cai et al. (2015) investigated the thermal conductivity of clay, silt, fine sand, and coarse sand in China's Nanjing region. Wang et al. (2017) showed that sand had higher thermal conductivity (1.44 W/m·K) than clay (0.69 W/m·K) and sandy loam (1.17 W/m·K). Alrtimi et al. (2016) reported that thermal conductivity increased with the degree of saturation. Liu et al. (2020) used forty data points correlating soil thermal conductivity with saturation (5–40 % water content). They observed a swift initial rise in mucky silty clay thermal conductivity with increased saturation, followed by stabilisation. The relationship showed exponential growth ($R^2 > 0.95$). Yang et al. (2022) found that the thermal conductivity increase sequence was: sand > composite of scrap tyre rubber and sand > shredded tyres. They explained that the particle arrangement transitioned

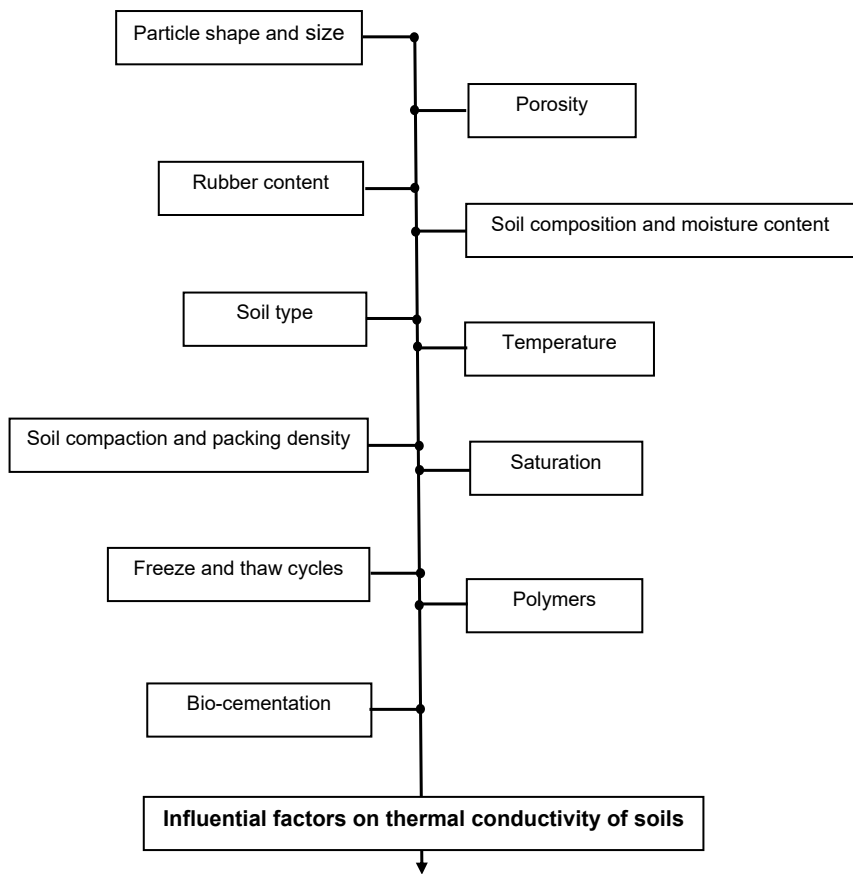


Fig. 1. Influential factors on the thermal conductivity of granular soils

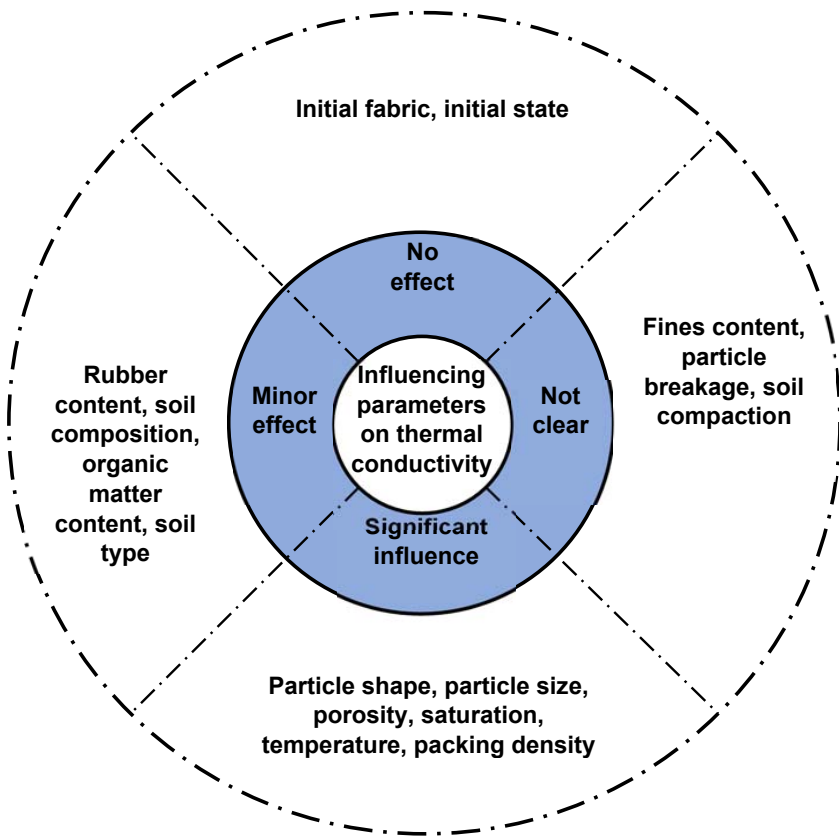


Fig. 2. Influencing parameter on the thermal conductivity of soils

from a ‘rubber-connected insulation layer’ to a ‘sand-encompassed conduction path’ as the sand-to-tyre ratio increased. Tang et al. (2008) studied the effects of dry density, water content, and saturation on American MX80 bentonite thermal conductivity, proposing a linear correlation with pore gas volume. Xu et al. (2016) explored bentonite-sand mixtures, while Liu et al. (2019) investigated bentonite-sand-graphite-fibre mixtures. Liu et al. (2020) reported an exponential relationship between water content and thermal conductivity in mucky silty clay at varying dry densities. Water addition forms thin films around particles, creating bridges between air gaps and particles, increasing the effective contact area and enhancing heat transfer. Beyond a specific water content threshold, thermal conductivity showed minimal variation across densities. Thermal conductivity is influenced by the effective contact area between particles (Brigaud and Vasseur, 1989; Cai et al., 2015). Studies have investigated the correlation between thermal conductivity and soil porosity (Tong et al., 2009; Wang et al., 2008). Liu et al. (2020) demonstrated that the thermal conductivity of mucky silty clay decreased exponentially with increasing porosity ($R^2 > 0.96$). Rubber addition decreases thermal conductivity, with important geotechnical implications. Lee and Shang (2013) found that rubber particle size and shredded tyre proportion significantly influenced thermal conductivity and anisotropy. Yang et al. (2022) demonstrated that shredded tyres significantly decrease sand thermal conductivity, suggesting applications in insulation layers. Particle shape affects thermal conductivity through arrangement effects (Gan et al., 2017; Fei et al., 2019). Xiao et al. (2020) reported that thermal conductivity increased with relative density for given particle shape parameters. Particle size has important effects on soil behaviour (Azaiez et al., 2022; Cherif Taiba et al., 2022; Mahmoudi et al., 2024) and, specifically, it significantly affects thermal conductivity; smaller particles generally have higher thermal conductivity due to increased contact facilitating heat transfer. Xiao et al. (2018) showed that thermal conductivity increased with the uniformity coefficient within the range $2.0 < Cu \leq 4.7$,

then increased gradually beyond $Cu > 4.7$. He et al. (2022) confirmed a good correlation between thermal conductivity and mean grain size of carbonate sand. Numerous predictive models have been developed (Lu et al., 2007). Johansen (1977) introduced the concept of normalised thermal conductivity, exploring the impacts of porosity and saturation. Côté and Konrad (2005) proposed novel relationships, while Chen (2014) developed empirical equations from 80 needle-probe tests. Alrtimi et al. (2016) showed that thermal conductivity fluctuations could be represented by logarithmic functions. Most prediction models yielded accurate results at lower porosity levels and high saturation ratios. Design parameters crucial for soil heat transfer include particle morphology, degree of saturation, and porosity. Additionally, this study moves well beyond a traditional literature review by combining a critical examination of the physical origins and governing mechanisms of soil thermal conductivity with the development of new semi-empirical predictive models. These models explicitly integrate the coupled effects of key soil parameters, specifically particle morphology, porosity, degree of saturation, and relative index. Built upon a rigorous synthesis of experimental data from published laboratory studies, the article uses this curated dataset to formulate quantitative relationships that reflect the interdependence of these variables. In doing so, it also identifies, clarifies, and reconciles discrepancies and inconsistencies present in the existing body of research. The paper is driven by real-world engineering demands in geotechnical, geoenvironmental, and geothermal applications, where reliable estimation of thermal properties is crucial. By merging in-depth critical analysis with original, data-informed modelling, this manuscript serves as both a scholarly synthesis and a practical tool, offering researchers and practitioners an enhanced framework for understanding and predicting the thermal behaviour of diverse soil types. Tables 1 and 2 present a summary of the key studies and the advantages and limitations of soil thermal conductivity research in the published literature.

Table 1. Summary of key studies on soil thermal conductivity

References	Soil Types	Key Parameters
Cai et al. (2015)	Clay, silt, fine sand, coarse sand	Particle size, soil type
Wang et al. (2017)	Sand, clay, sandy loam	Soil type, saturation
Yang et al. (2022)	Sand, tyre-sand mixtures	Tyre content, particle arrangement
Tang et al. (2008)	MX80 bentonite	Dry density, water content, saturation
Xu et al. (2016); Liu et al. (2019)	Bentonite-sand-graphite fibres	Additive effects
Côté and Konrad (2005)	Silica sands	Porosity, particle size
Johansen (1977)	Theoretical	Porosity, saturation
Chen (2014)	Various (80 tests)	Saturation, porosity

Table 2. Advantages and limitations of key thermal conductivity studies in the published literature

References	Advantages	Limitations / Gaps
Cai et al. (2015)	Real field soils; comparative analysis across soil types	Limited control over fabric; no quantitative model proposed
Wang et al. (2017)	Clear comparative data; practical relevance	Small dataset; no porosity or density control reported
Yang et al. (2022)	Novel application (recycled materials)	Non-natural material; limited to insulation context
Tang et al. (2008)	Relevant for nuclear waste disposal	Only bentonite; narrow applicability
Xu et al. (2016); Liu et al. (2019)	Tailored for barrier design	Complex mixtures; not representative of natural soils
Côté and Konrad (2005)	High-precision lab setup; temperature control	Excludes fines; no saturation >80 % tested
Johansen (1977)	Foundational model; widely used	Empirical; less accurate at low saturation
Chen (2014)	Large dataset; practical correlations	Limited mechanistic insight; model not universal

Proposal of Novel Predictive Models Based on Data from a Literature Review

All the data incorporated in this review were drawn exclusively from controlled laboratory experiments reported by the original authors, each employing distinct but well-established techniques to measure soil thermal conductivity under carefully regulated conditions. Côté et al. (2011) conducted their experiments in a temperature-controlled cold room using a custom-built thermal conductivity cell: dry soil was compacted into thin cylindrical PVC molds (10.1 cm in diameter and 7.5 cm in height) and placed between two 3-cm-thick Pyrex glass disks functioning as heat flux meters; high-precision thermistors were embedded at the center of each disk face, positioned within fractions of a millimeter from the soil-disk interfaces, to accurately capture the steady-state temperature gradient across the specimen. Alrtimi et al. (2016) utilised a steady-state divided-bar apparatus grounded in Fourier's law of heat conduction, where a uniform one-dimensional heat flux was applied through two identical, vertically stacked soil samples, enabling the determination of thermal conductivity across a range of saturation levels by measuring the resulting temperature drop along the heat flow path. Xiao et al. (2020) adopted a transient approach using a vertically oriented thermal needle probe system; their samples were prepared via the under-compaction method, a layer-by-layer compaction technique that minimises density gradients and ensures uniform fabric, allowing precise control over initial dry density, porosity, and degree of saturation during testing. Finally, Liu et al. (2020) and He et al. (2022) both employed a multifunctional thermal needle probe system based on the transient line heat source method, in which a short-duration electrical pulse heats a needle embedded in the soil, and the resulting temperature rise over time is recorded to calculate thermal conductivity; this technique is particularly effective

for capturing the influence of moisture content, density, and soil structure under near-instantaneous, minimally invasive conditions. While these studies vary in their methodological details, ranging from steady-state to transient techniques and differing sample preparation protocols, all were conducted under controlled laboratory settings, ensuring high data quality and reproducibility, which forms a robust foundation for the comparative analysis and model development presented in this review. In addition, all the experimental data used in this study were obtained from studies in which the original researchers employed cohesionless soils and are valid only within the following experimentally covered ranges summarised in Table 3.

Thermal Conductivity as a Function of Porosity, Degree of Saturation and Effective Diameter

To formulate multi-variable equations connecting thermal conductivity (λ) with porosity (n), degree of saturation (S_r), and effective diameter (D_{10}), we utilised data from Liu et al. (2020) and Alrtimi et al. (2016). This enabled the prediction of thermal conductivity as a function of porosity and saturation. Additionally, we examined Côté et al. (2011) data to assess the relationship between thermal conductivity, porosity, and effective diameter. Fig. 3 confirms that thermal conductivity rises with decreasing porosity and increasing effective diameter. The 3D plots illustrate that thermal conductivity increases with elevated saturation and reduced porosity in both studies. Figs. 4 and 5 demonstrate robust correlations between thermal conductivity, porosity, and saturation in compiled data from Liu et al. (2020) and Alrtimi et al. (2016), with high determination coefficients ($R^2 = 0.95$ and 0.84).

However, the correlation between thermal conductivity, porosity, and effective diameter in Côté et al. (2011) yields a lower determination coefficient ($R^2 = 0.62$) compared to Liu et al. (2020) and Alrtimi

Table 3. Boundary conditions of the proposed thermal conductivity models

Parameter	Symbol	Range	Source Studies
Effective grain size	D_{10} (mm)	0.087 – 2.70	Côté et al. (2011)
Mean grain size	D_{10} (mm)	0.16 – 3.16	He et al. (2022)
Porosity	n	0.327 – 0.640	Liu et al. (2020); Alrtimi et al. (2016)
Degree of saturation	S_r	1.5 % – 100 %	Liu et al. (2020); Alrtimi et al. (2016)
Relative index	I_d	0 – 1	He et al. (2022); Xiao et al. (2020)
Sphericity	S	0.48 – 0.60	He et al. (2022)
Overall regularity	OR	0.822 – 0.960	Xiao et al. (2020)
Aspect ratio	AR	0.715 – 0.969	Xiao et al. (2020)
Convexity	C_x	0.950 – 0.995	Xiao et al. (2020)
Thermal conductivity	λ (W/m·K)	0.094 – 2.475	All sources

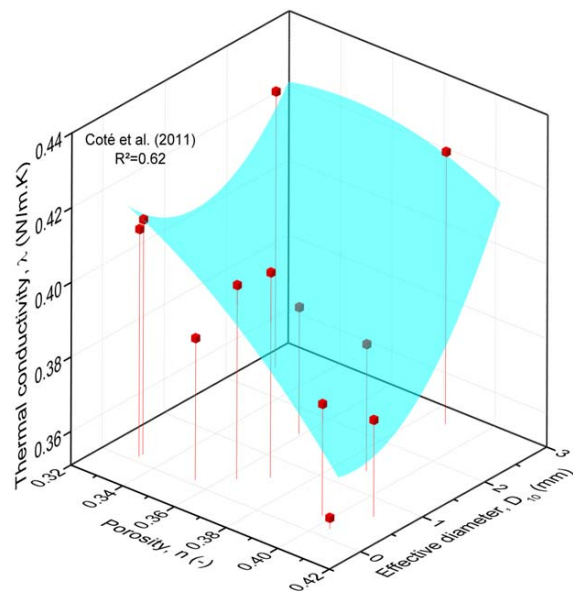


Fig. 3. Thermal conductivity versus porosity and effective diameter

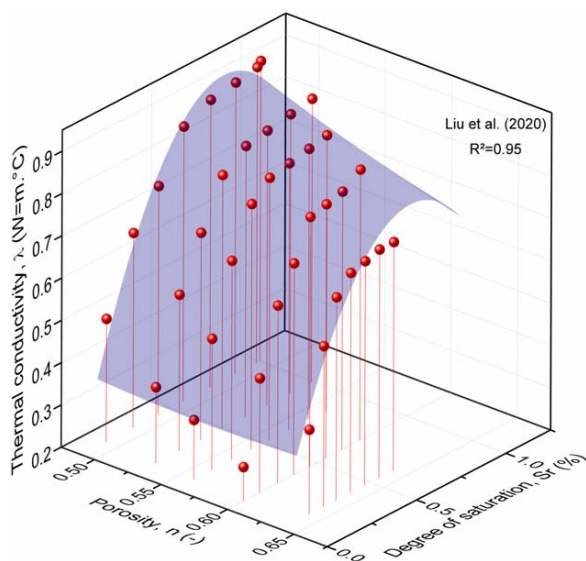


Fig. 4. Thermal conductivity versus porosity and degree of saturation

et al. (2016). This underscores the significant impact of coupled porosity and saturation effects on thermal conductivity, emphasising their greater influence compared to the combined effects of porosity and effective diameter. Understanding coupled porosity and saturation effects is crucial for accurately predicting thermal conductivity variations. When porosity and saturation are considered together, their combined effects exhibit a synergistic impact on thermal conductivity. Simultaneous variation in both parameters results in more pronounced thermal conductivity changes compared to single-factor consideration. The proposed multi-variable equations for thermal conductivity as functions of porosity (n), degree of saturation (S_r), and effective diameter (D_{10}) from three literature studies are as follows:

$$\lambda = 1.4 \times (n)^2 - 1.15 \times (S_r)^2 - 1.51 \times (n) + 2.35 \times (S_r) - 1.09 \times (n) \times (S_r) + 0.60; \quad (1)$$

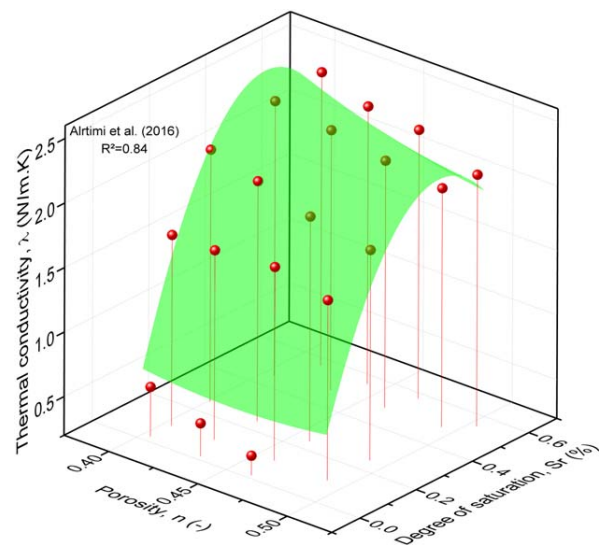


Fig. 5. Thermal conductivity as function of porosity and degree of saturation

$$\lambda = 19.67 \times (n)^2 - 9.85 \times (Sr)^2 - 17.66 \times (n) + 11.52 \times (Sr) - 6.86 \times (n) \times (Sr) + 4.51; \quad (2)$$

$$\lambda = -3.39 \times (n)^2 + 0.009 \times (D_{10})^2 + 1.86 \times (n) - 0.08 \times (D_{10}) + 0.19 \times (n) \times (D_{10}) + 0.17. \quad (3)$$

Thermal Conductivity as a Function of Relative Index and Particle Size

In this section, we present a multi-variable function in which thermal conductivity (λ) serves as the dependent variable, while the independent predictor variables are the relative index (I_d) and particle size represented by the mean diameter (D_{50}). To assess the accuracy and effectiveness of using thermal conductivity as the dependent variable, we performed a multi-variable analysis using compiled data extracted from the research of He et al. (2022). The 3D plots show that as the relative index of the materials increases, there is an enhancement in their thermal conductivity (Fig. 6). Additionally, when the mean diameter of the materials decreases, this is associated with an increase in thermal conductivity. This can be interpreted as greater efficiency in heat transfer within the materials, likely due to improved contact between particles or a reduction in the mean free path for heat carriers, ultimately leading to higher thermal conductivity values. Through this analysis, we evaluate the connection between thermal conductivity, relative index, and mean diameter, providing valuable insights into the accuracy and effectiveness of the proposed multi-variable function. A polynomial function was chosen as the mathematical representation for the investigated relationship. The results highlight the suitability

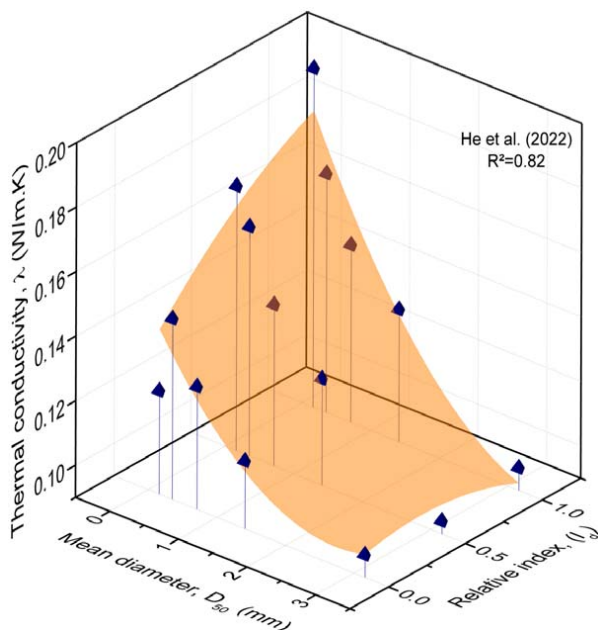


Fig. 6. Thermal conductivity versus mean diameter and relative index

of including the relative index and mean diameter when studying the thermal conductivity of the tested materials, yielding a coefficient of determination of $R^2 = 0.82$. The proposed multi-variable equation for thermal conductivity (λ) in terms of mean diameter (D_{50}) and relative index (I_d) for the tested soils is expressed as follows:

$$\lambda = -0.007 \times (D_{50})^2 - 0.017 \times (I_d)^2 - 0.04 \times (D_{50}) + 0.06 \times (I_d) + 0.015 \times (D_{50}) \times (I_d) + 0.15. \quad (4)$$

Thermal Conductivity as a Function of Relative Index and Particle Shape

The objective was to create multi-variable equations that establish a correlation between thermal conductivity (λ), relative index (I_d), and particle shape characteristics, specifically sphericity and regularity (S and ρ), using data collected from the study of He et al. (2022). The results indicate a strong correlation between thermal conductivity and both the relative index and particle shape properties (S and ρ). The observed increase in thermal conductivity with rising relative index and favourable particle shape characteristics can be attributed to improved heat transfer efficiency within the materials. A higher relative index suggests a more efficient transfer of thermal energy, and favourable particle shapes, such as increased sphericity and regularity, likely contribute to enhanced contact and conductivity pathways between particles. These factors collectively result in a higher thermal conductivity, indicating a more effective transmission of heat through the material (Fig. 7).

The use of an exponential function for regularity and a polynomial equation for sphericity as mathematical representations of the studied relationship was driven by their suitability in capturing complex, non-linear interactions among variables. This choice enables the modelling of intricate behaviours observed in thermal conductivity concerning both relative index and particle shape characteristics. The results obtained underscore the significance of incorporating both relative index and particle shape properties, specifically sphericity and regularity, when examining the thermal conductivity of the tested materials. In particular, when focusing on sphericity and regularity, the coefficients of determination (R^2) reached notable values of 0.86 and 0.87, respectively. These high R^2 values indicate strong correlations, suggesting that the proposed multi-variable functions effectively capture the underlying patterns in the data. The multi-variable equations proposed for thermal conductivity (λ), expressed as functions of relative index and particle shape properties (S and ρ) for the tested soils, provide quantitative representations of the relationship. These equations serve as valuable tools for predicting thermal conductivity based on the specified variables, contributing to a more nuanced

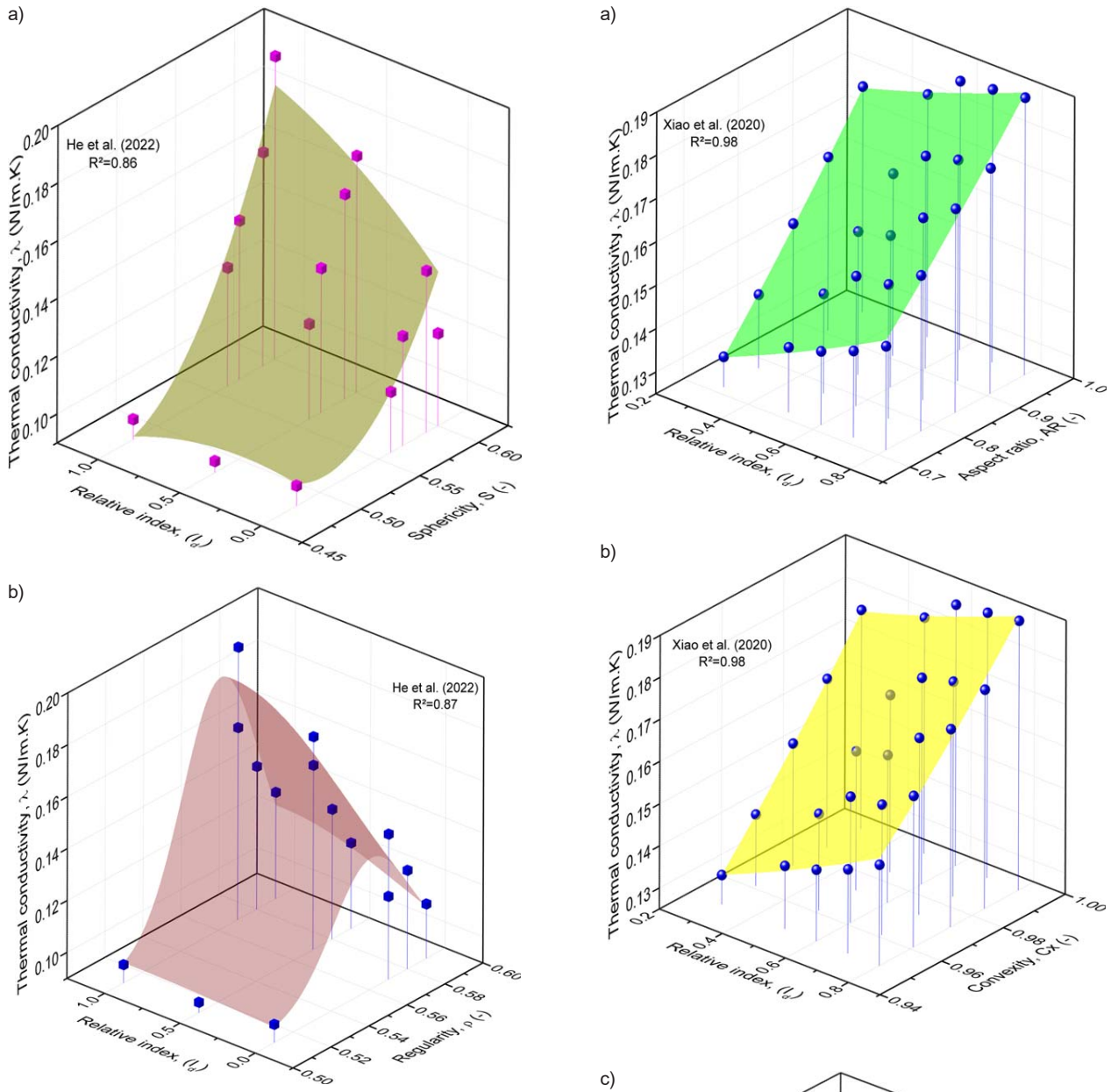


Fig. 7. Thermal conductivity versus relative index and particle shape characteristics: Sphericity; (b) regularity

understanding of the intricate processes occurring within the soils:

$$\lambda = 5.2 \times (S)^2 - 0.017 \times (I_d)^2 - 5.26 \times (S) - 0.18 \times (I_d) + 0.40 \times (I_d) \times (S) + 1.41; \quad (5)$$

$$\lambda = 0.09 \times e^{(-0.5 \times (\rho - 0.56)^2) - (0.5 \times (I_d - 0.96)^2)} + 0.094. \quad (6)$$

Moreover, Fig. 8 depicts correlations between thermal conductivity (λ) and relative index (I_d) with three particle shape properties: aspect ratio (AR), convexity (Cx), and overall regularity (OR) using data from Xiao et al. (2020). Results show that an increase in relative index and favourable particle shape characteristics substantially increases thermal conductivity. Increased thermal conductivity with

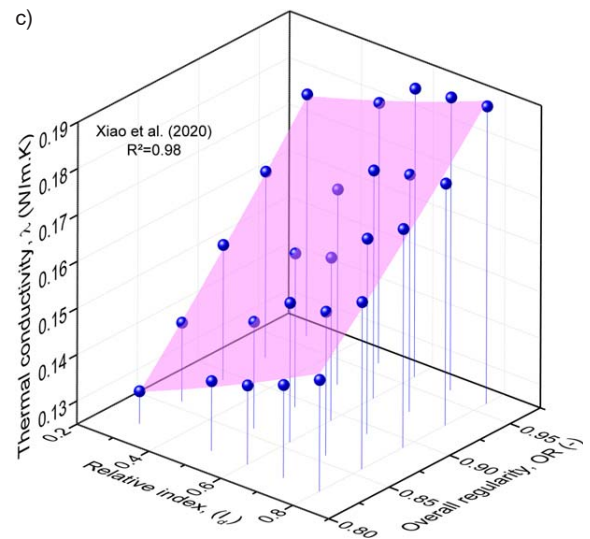


Fig. 8. Thermal conductivity versus relative index and particle shape characteristics: aspect ratio; (b) convexity; (c) overall regularity

higher relative index and favourable particle shape characteristics results from improved heat transfer efficiency. Higher relative index indicates more effective thermal energy transfer, meaning better heat conduction and higher overall thermal conductivity. Improved particle shape characteristics — higher aspect ratio, increased convexity, and overall regularity — contribute to better particle contact and alignment. Enhanced contact creates more efficient heat conduction pathways, increasing thermal conductivity. This analysis assesses relationships between thermal conductivity (λ) and independent variables (I_d , AR , C_x , OR), providing valuable insights into the multi-variable equation precision and effectiveness. Polynomial functions were selected as the mathematical representation for the explored correlations. Results underscore the appropriateness of incorporating (I_d , AR , C_x , OR) when investigating thermal conductivity, yielding high determination coefficients (R^2) of 0.98 for (AR , C_x , OR). The proposed multi-variable equations for thermal conductivity (λ), expressed in terms of particle shape properties (AR , C_x , OR) and relative index (I_d) for the tested soils, are as follows:

$$\lambda = 0.009 \times (I_d)^2 + 0.22 \times (OR)^2 + 0.09 \times (I_d) - 0.04 \times (OR) - 0.07 \times (I_d) \times (OR) + 0.01; \quad (7)$$

$$\lambda = 0.009 \times (I_d)^2 + 0.06 \times (AR)^2 + 0.05 \times (I_d) + 0.0 \times (AR) - 0.04 \times (I_d) \times (AR) + 0.03; \quad (8)$$

$$\lambda = 0.009 \times (I_d)^2 + 2.46 \times (C_x)^2 + 0.23 \times (I_d) - 3.72 \times (C_x) - 0.22 \times (I_d) \times (C_x) + 1.44. \quad (9)$$

Validation of the Newly Proposed Models

The validation procedure for the multi-variable equations linking predicted to measured thermal conductivity values from literature involved a thorough analysis. Three distinct models were collected directly from the original published studies cited in this review article. All data points plotted on the x-axis correspond to the actual measured thermal conductivity values reported in these peer-reviewed sources. The y-axis, in contrast, shows the values predicted by the new models proposed in this study, enabling a direct validation of model performance against independent experimental data. Mean Absolute Error (MAE) is determined by computing the absolute errors, summing them, and dividing by the total number of observations. For equations (1)–(9), the calculated MAE values are 0.003, 0.009, 0.001, 0.001, 0.009, 0.002, 0.006, 0.009, and 0.0003, respectively. MAE indicates the average magnitude of discrepancies between predicted and actual values, providing insights into equation accuracy. Root Mean Square Error (RMSE) is computed by summing squared errors, dividing by the total number of observations, and taking the square root. RMSE values for the equations are

0.02, 0.04, 0.005, 0.003, 0.03, 0.009, 0.03, 0.04, and 0.001, respectively. RMSE measures the standard deviation of differences between predicted and actual values, reflecting the overall error magnitude. Lower RMSE indicates better agreement between predicted and observed data. The coefficient of determination (R^2) was calculated for each equation, yielding values ranging from 0.98 to 0.99 for Equations (1)–(9), as depicted in Figs. 9, 10, and 11. R^2 indicates the proportion of the variance in thermal conductivity that is explained by the independent variables (particle morphology, porosity, degree of saturation, and relative index). The obtained R^2 values affirm a substantial correlation between thermal conductivity and the evaluated parameters (particle shape properties, n , S_r , I_d , and particle size), aligning with the predictions. These validation outcomes underscore the dependability and efficacy of the proposed multi-variable equations. Small MAE and RMSE values signify high precision in predicting thermal conductivity based on the studied independent variables. High R^2 values suggest that the equations elucidate significant portions of variation in thermal conductivity. This validation study provides comprehensive insights into the intricate relationships between thermal conductivity and the factors affecting soil heat transfer paths, contributing to a deeper understanding of these systems and their practical applications.

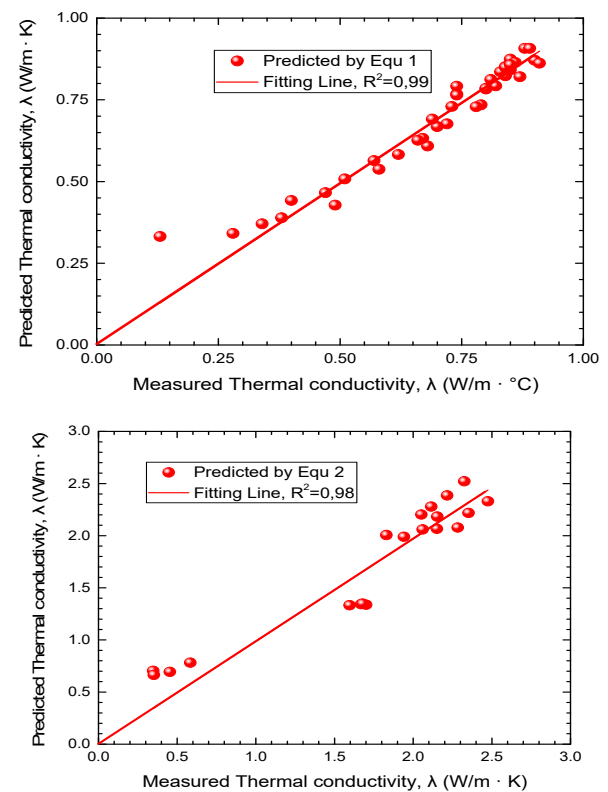


Fig. 9. Predicted thermal conductivity (Equations (1)–(3)) plotted against measured thermal conductivity

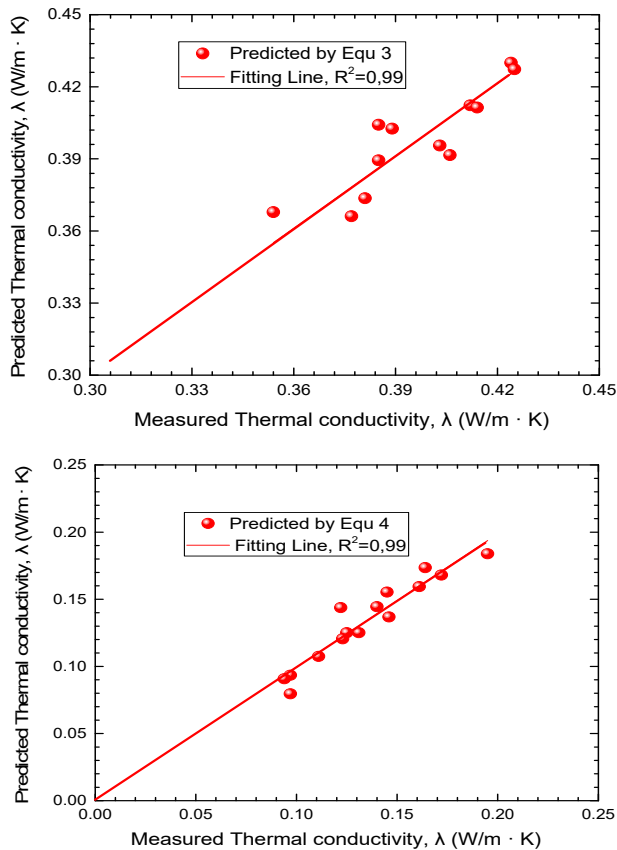


Fig. 10. Predicted thermal conductivity (Equations (4)–(6)) plotted against measured thermal conductivity

Conclusion

Studying the factors affecting the thermal conductivity of granular soils is crucial in geotechnical engineering, environmental science, and geothermal energy systems. Understanding how particle morphology, porosity, degree of saturation, and relative index affect thermal conductivity helps in designing efficient geothermal systems and predicting soil heat transfer. Engineers can develop more effective systems by considering the unique thermal behaviour of granular soils. This paper has presented innovative formulations for estimating soil thermal conductivity that serve as valuable predictive tools. The proposed multi-variable functions provide comprehensive approaches for accurately determining thermal conductivity. Assessing the accuracy of the proposed equations via performance evaluation is crucial, involving error computation and

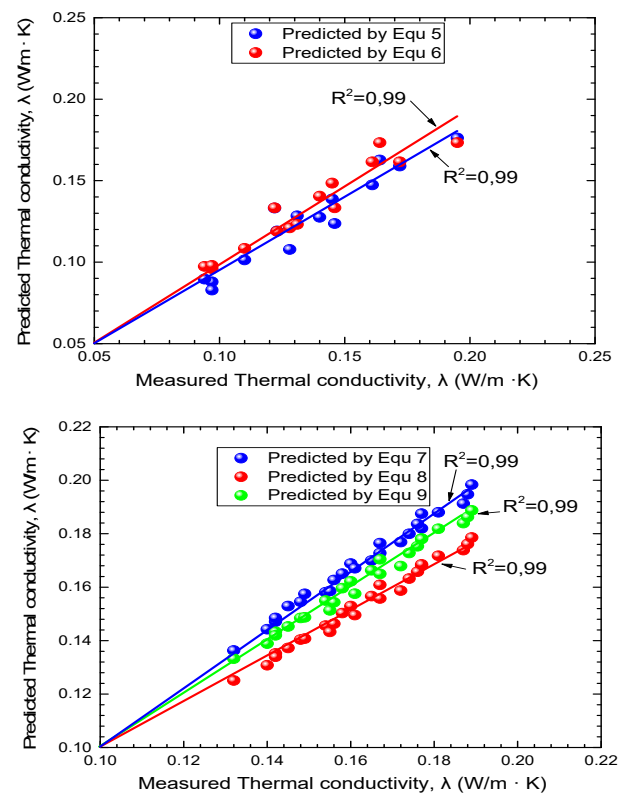


Fig. 11. Predicted thermal conductivity (Equations (7)–(9)) plotted against measured thermal conductivity

metrics such as MAE and RMSE to ascertain their reliability. The validation study offers insights into the relationships between thermal conductivity and the independent variables (particle morphology, porosity, degree of saturation, and relative index), enhancing understanding and highlighting practical implications. This review serves as a valuable resource connecting theory with application for scientific inquiry and engineering practice. Continued research into other influential parameters affecting granular soil thermal conductivity is essential for advancing knowledge and promoting practical applications.

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КРИТИЧЕСКИЙ ОБЗОР ВЛИЯНИЯ МОРФОЛОГИИ ЧАСТИЦ И ПОРИСТОСТИ НА ТЕПЛОПРОВОДНОСТЬ ПОЧВЫ

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Аннотация

Введение. Данный критический обзор подчеркивает важность исследования в обширном корпусе литературы по изучению грунтов таких ключевых факторов, как морфология частиц и пористость. Углубленное понимание влияния этих элементов на теплопроводность грунта играет важную роль в развитии геотехнических и экологических областей знаний. **Методы.** Данный обзор обобщает результаты широкого спектра исследований и подчеркивает сложную природу теплопроводности грунтов, а также необходимость тщательного изучения этих параметров. Каждый фактор играет решающую роль в определении поведения теплопередачи в грунтах. На основе углубленного анализа существующих исследований данная статья подчеркивает необходимость систематического изучения этих переменных для разрешения противоречий, восполнения пробелов в знаниях и совершенствования прогностических моделей для применения в геотехнических и экологических исследованиях. **Заключение.** Недавно разработанные многомерные функции предлагают надежную основу для прогнозирования теплопроводности грунтов путем интеграции этих значимых параметров. Данный всесторонний обзор, связывающий теорию с практическим применением, служит важным ресурсом, поддерживающим как научные исследования, так и инженерную практику.

Ключевые слова: теплопроводность, зернистые грунты, факторы, критический обзор, предлагаемые модели.

ASSESSMENT OF BUFFETING IN THE WAKE EFFECT ON BRIDGE AERODYNAMIC STABILITY BASED ON EXPERIMENTAL MODELLING

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Abstract

Introduction. This paper addresses the problem of aerodynamic stability of bridge structures, specifically the phenomenon of buffeting. The relevance of the study is driven by regular accidents and failures of bridges, among the causes of which are insufficient consideration of wind effects and aerodynamic instability of structures. The aim of this work is to experimentally assess the aerodynamic stability of a two-span road bridge (with a central span length of 130 m) considering the possible occurrence of buffeting. **Methods.** The research methodology includes manufacturing a physical model of the superstructures with geometric and dynamic similarity, conducting static tests to determine aerodynamic coefficients, and dynamic tests of the aerodynamic stability of the model. **Key results.** Experimental studies on section models have shown that buffeting can occur in a superstructure located in the aerodynamic wake behind another — with the inclination of the structure relative to the oncoming flow and the difference in the overall dimensions of the fairings playing a critical role. Experimental modelling in wind tunnels remains the key method for assessing the possibility of aerodynamic instability phenomena in long-span bridges. Refinement of computational models will reduce the risks of bridge structure failures caused by wind effects.

Keywords: buffeting, experimental modelling, wind tunnels, wind effects, aerodynamic instability, bridges.

Introduction

The analysis of recent disasters is consistent with the findings of studies (Maistrenko et al., 2017; Maistrenko et al., 2018; Ovchinnikov et al., 2017; Ovchinnikov et al., 2018): accidents and failures of transport structures represent a persistent global problem, independent of the level of economic development of countries. Poddaeva (2022) notes that such incidents have been recorded in the past, continue to occur today, and are likely to persist in the future, with their frequency potentially correlating with the total number of transport facilities. Among the key risk factors confirmed by both Russian and foreign experts, insufficient consideration of wind effects stands out. In particular, the series of works (Maistrenko et al., 2017; Maistrenko et al., 2018; Ovchinnikov et al., 2017; Ovchinnikov et al., 2018), representing one of the most comprehensive analyses of bridge structure failures, classifies the underestimation of wind loads and aerodynamic instability as an independent group of causes of disasters.

The increase in spans and flexibility of modern bridges (especially cable-stayed and suspension bridges) enhances susceptibility to buffeting. Even structures that are stable under static wind loads may

experience critical dynamic effects in the wake. The resulting losses of stability of bridge structures, up to and including failure, demonstrate that for bridge structures, verification of aerodynamic stability is one of the key stages in their design.

The design of bridge structures necessarily includes a stage of ensuring their aeroelastic stability. The regulatory framework of the Russian Federation defines the procedure for investigating wind effects, which is established in GOST R 59625–2022 “Public Roads. Bridge Structures. Rules for Calculation and Confirmation of Aeroelastic Stability”. In accordance with clause 5.1 of the standard, the consideration of wind effects should cover the following aspects:

- static wind effect on the structure and its elements;
- dynamic effect, including wind gusts, squalls, and the influence of thunderstorm fronts;
- aeroelastic interaction of the flow with the superstructure.

Calculations for static and dynamic loads are performed according to GOST 33390; SP 20.13330.2016; SP 35.13330.2011.

Special attention should be paid to the phenomenon of buffeting — one of the least studied forms of aeroelastic instability (Kazakevich,

2020) — which occurs under turbulent conditions or in the wake behind structural elements due to the superposition of heterogeneous aerodynamic forces. A characteristic feature of buffeting is an increase in oscillation amplitude (“build-up”) due to wake impacts. The high danger of this phenomenon is due to its insufficient theoretical development (Kazakevich, 2020).

The requirements for ensuring aerodynamic stability are specified in clause 12 of GOST R 59625–2022:

$$\frac{S_0}{H} > 50. \quad (1)$$

where S_0 is the clear distance between structures or individual structural elements, and H is the characteristic dimension of the structure across the flow, in the wake of which the structure under consideration is located, m.

Clause 12.2 of GOST R 59625–2022 prescribes that if condition (1) is not satisfied, the results of model tests in wind tunnels should be followed.

Soloviev (2016) states that the influence of buffeting can be neglected if the distance between bridge structures exceeds 10 times the width of the central span of the bridge. However, if two practically identical superstructures are located in the same plane and separated only in the longitudinal direction by a gap of less than 1 m, the wind force on the windward side can be calculated in the same way as for a composite structure. In other cases, it is necessary to investigate the mutual influence of bridges.

Bridge aeroelasticity plays a key role in long-span bridge buffeting response, and therefore correct modelling of self-excited forces in turbulent flow is crucial (Barni et al., 2022). Several studies (Diana et al., 1993; Diana and Omarini, 2020; Chen and Kareem, 2001) have also demonstrated that the aeroelastic behaviour of most bridge cross-sections is significantly affected by a variation of the mean angle of attack. Barni et al. (2022) propose a time-domain framework based on the 2D self-excited force model, yielding a time-variant state-space formulation of the buffeting problem. In the research by Gao et al. (2024), the phenomenon of buffeting in the wake is investigated using numerical modelling. The results indicate that

the wake-induced vibration of the suspender exhibits a lock-in phenomenon with large cross-wind amplitudes at specific incoming wind velocities. Morais da Costa et al. (2022) propose an improved bridge buffeting theory with an emphasis on skew wind directions, for both turbulence- and motion-dependent forces. Traditional models often consider wind acting strictly along or across the bridge. The new theory accounts for skew angles of attack and simultaneously models the influence of turbulence and “feedback”: when the motion of the bridge itself changes the aerodynamic forces acting upon it.

Thus, the primary method for assessing the aerodynamic stability of bridge structures remains experimental modelling in wind tunnels. Further development of the theory and practice of investigating superstructures for buffeting phenomena will improve the accuracy of computational models, enhance regulatory design requirements, and reduce the risks of bridge failures due to insufficient consideration of wind effects.

Methods

As the object of study for the possible occurrence of buffeting, a two-span road bridge with a central span length of 130 m was selected. The cross-sectional layout of the bridge is shown in Fig. 1. The distance between the two spans is 1.1 m. According to Fig. 1, the criterion for ensuring aerodynamic stability is not satisfied; therefore, the verification of aerodynamic stability must be carried out based on the results of model tests in wind tunnels.

In accordance with clause 5.48 of SP 35.13330.2011 “Bridges and Pipes”, the assessment of the aerodynamic stability of a bridge requires modelling of the longest span section — as the most susceptible to dynamic wind effects. The methodology of aerodynamic experimental studies is described in detail in reference (Poddaeva, 2022). The experiments are performed at the Unique Scientific Facility “Large Research Gradient Wind Tunnel” of NRU MGSU. The physical model of the superstructures is manufactured at a scale of 1:64.2 from sheet aluminium. The choice of material ensures high geometric similarity accuracy, lightness, and rigidity of the structure. The resulting model meets the requirements of clause 15.4.2 of

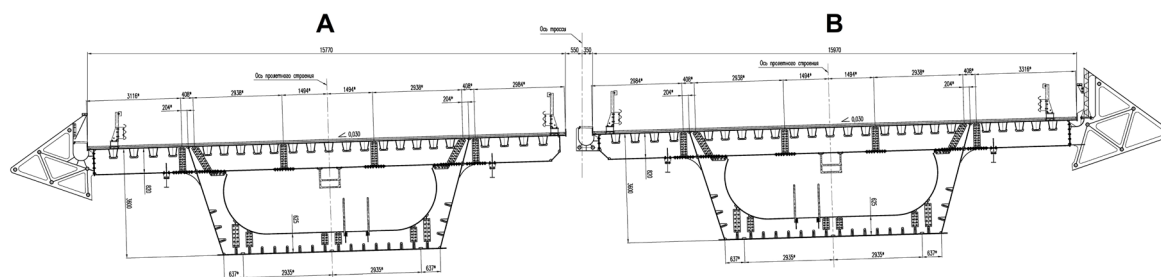


Fig. 1. Typical cross-sectional layout of the bridge superstructure

GOST R 59625–2022 regarding geometric similarity and mass distribution relative to the full-scale object. Similarity in Newton and Scruton numbers is maintained. The manufactured model (Fig. 2) corresponds to the full-scale object in the following parameters: geometric similarity; correspondence of mass distribution; correspondence of geometric centres of mass; which fully satisfies the requirements of GOST R 59625–2022. The calculated similarity criteria values are presented in Table 1.

The designed model corresponds to the full-scale object in the following parameters:

- geometric similarity;
 - correspondence of mass distribution;
 - correspondence of geometric centres of mass;
- which fully satisfies the requirements of GOST R 59625–2022.

The correspondence of the section model to the similarity laws ensures the representativeness of the aerodynamic test results. In this case, the actual behaviour of the superstructure is adequately reflected by the behaviour of its model

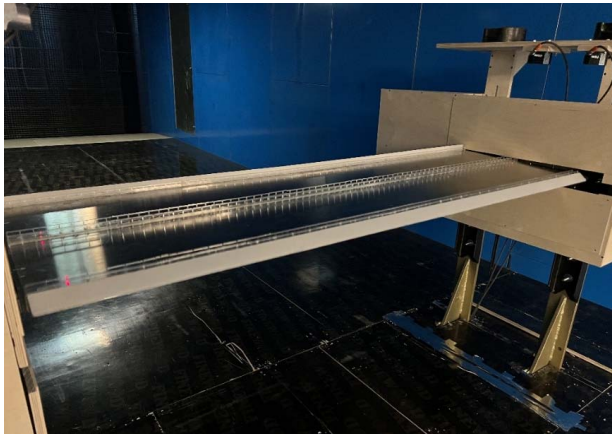


Fig. 2. Model of the investigated object

in the wind tunnel, which allows direct extrapolation of experimental data to the full-scale object. Dynamic similarity of the model and its frequency characteristics are modelled by specialised springs of the measuring stand.

When investigating the dynamic behaviour of the downstream superstructure, the recommended standard values of oscillation frequencies were adopted as reference points for verification of experimental data:

- the frequency of the first (bending) mode of oscillation was set at $f_{bend} = 0.68$ Hz, which corresponds to typical parameters of similar structures;

- the frequency of the fifth (torsional) mode of oscillation was adopted as $f_{tors} = 3.38$ Hz, reflecting the expected response of the system to torsional effects.

An important parameter characterising the dissipative properties of the structure is the logarithmic decrement of damping. At small oscillation amplitudes, its value was $\delta = 0.02$, which is typical for rigid metal structures with low internal damping.

For a comprehensive assessment of damping properties across the entire range of investigated regimes, data on the logarithmic decrement of damping are presented in Table 2. These values allow for: assessing the change in damping depending on the oscillation amplitude; comparing experimental results with computational models; confirming the correctness of the selected reference frequencies.

The scales of wind velocity, geometric dimensions, and frequencies are determined based on the ratio of the model and full-scale bridge dimensions — the corresponding data are presented in Table 3. The results of oscillation frequency measurements of the superstructure model, performed on the measuring stand, are shown in Figs. 3–5.

Table 1. Calculated similarity criteria values

	Model	Full Scale	Model / Full Scale
Newton similarity	$Nw_{mod} = 942$	$Nw_{full} = 974$	$\frac{Nw_{mod}}{Nw_{full}} = 0.97$
Scruton similarity	$Sc_{mod} = 37.68$	$Sc_{full} = 38.96$	$\frac{Sc_{mod}}{Sc_{full}} = 0.97$

Table 2. Logarithmic decrement of damping values at different oscillation amplitudes

Oscillation Amplitude	Model Damping Decrement Value
Amplitudes around 50 mm in full-scale equivalent	0.02
Near-zero amplitudes at the end of the decay process	0.018
Amplitudes around 150 mm in full-scale equivalent	0.027
Amplitudes around 300 mm in full-scale equivalent	0.04
Amplitudes around 400–500 mm in full-scale equivalent	0.06

Table 3. Ratios for the model and full-scale object

	Oscillation Mode	Full-Scale Object	Model	Velocity Scale U^*
Full-scale object and model frequencies	Bending (1st mode)	0.68 Hz	9.15 Hz	4.77
	Torsion	3.38 Hz	16.7 Hz	12.9

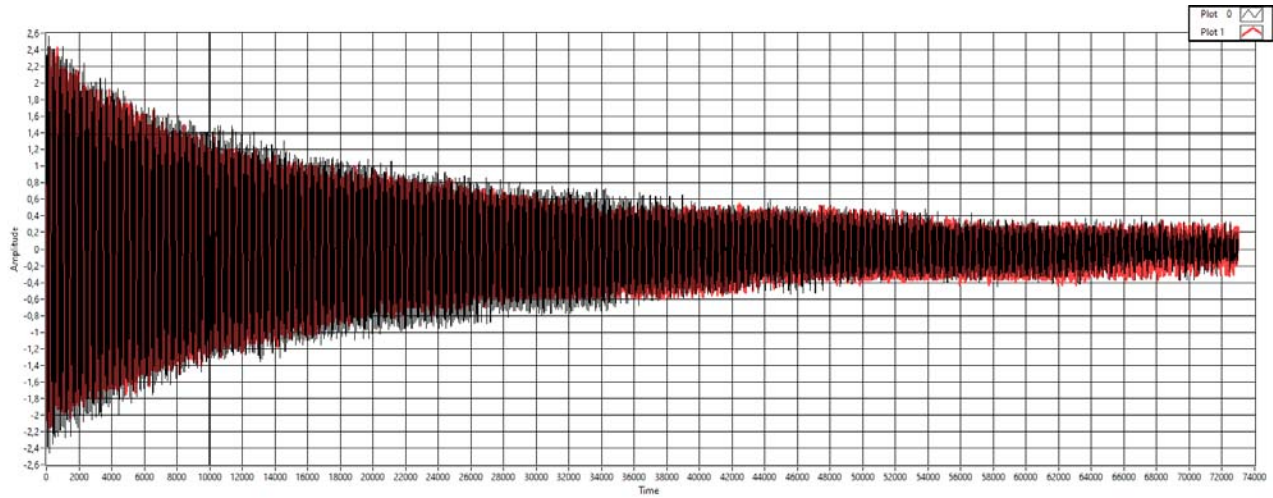


Fig. 3. Damped oscillatory process

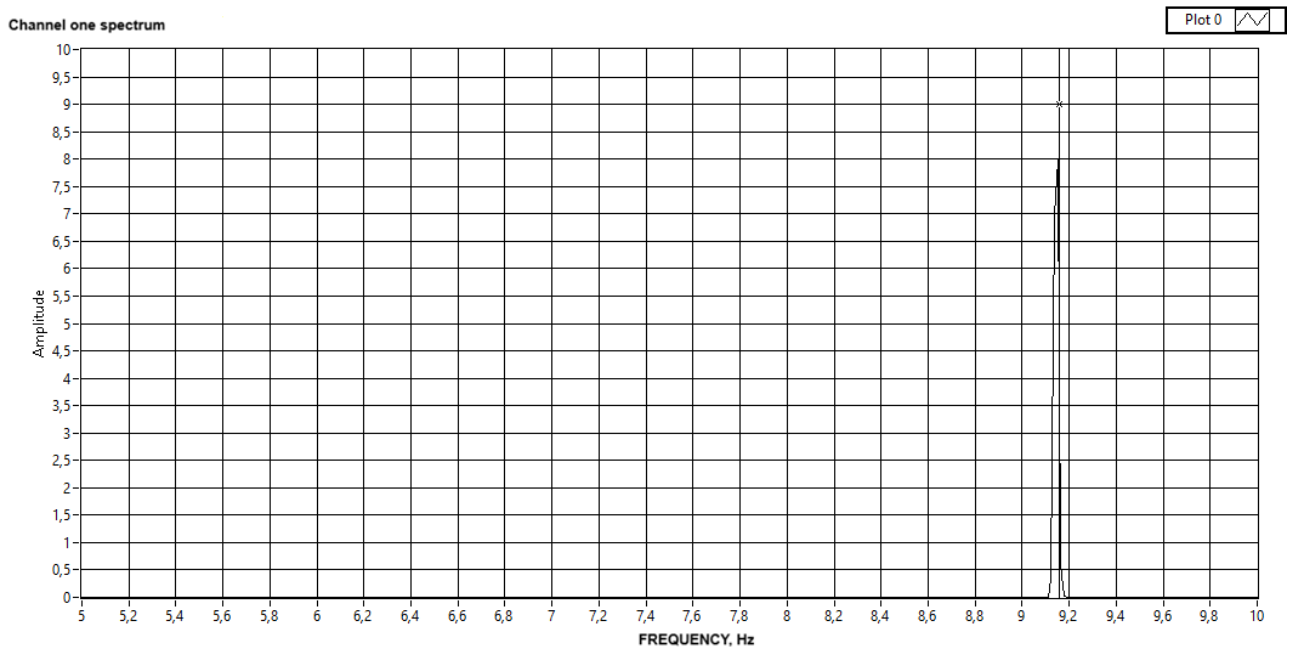


Fig. 4. Power spectral density for bending oscillations

The calculation of the wind velocity scale for bending oscillations was performed using the classical Strouhal formula:

$$U^* = L^* \cdot f^* = 64,2 \cdot \frac{0,68}{9,15} = 4,77 \quad (2)$$

Preliminary aerodynamic tests of the bridge model confirmed that the experimental Strouhal number (calculated based on the flow velocity and oscillation frequency) corresponds to analytical

estimates for similar structures. The layout of the force-moment sensors is shown in Fig. 6, and the range of considered angles of attack of the oncoming wind flow is shown in Fig. 7. Preliminary tests of the bridge model in the flow showed that the obtained Strouhal number (calculated from the flow velocity and oscillation frequency) corresponds to the analytical estimate for similar structures.

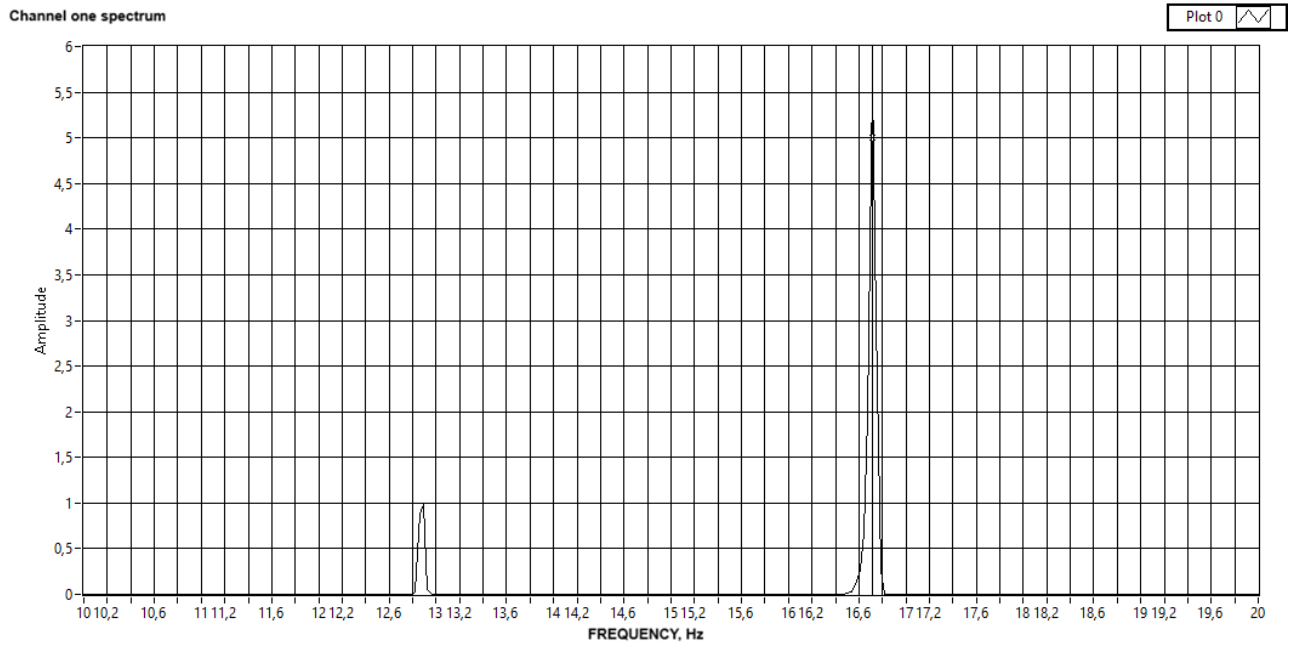


Fig. 5. Power spectral density for torsional oscillations

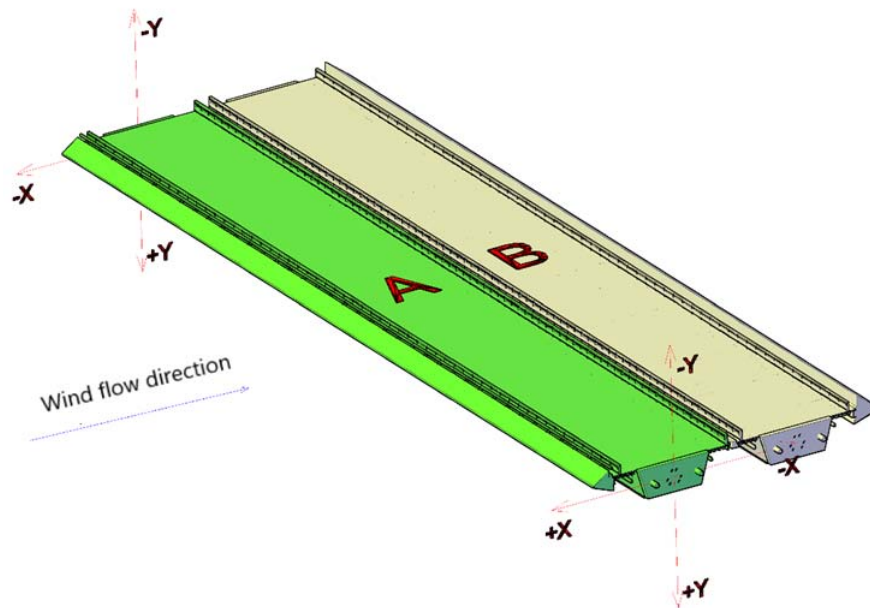


Fig. 6. Placement of force-moment sensors during static tests

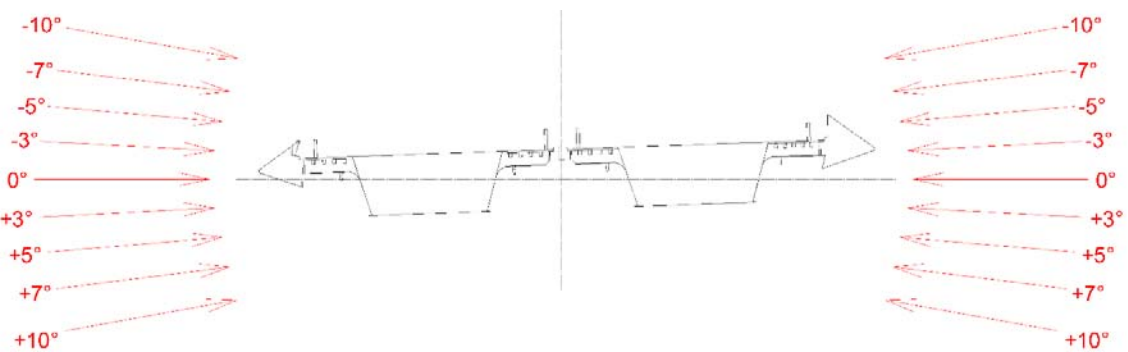


Fig. 7. Angles of attack of the oncoming wind flow considered during experimental studies

In accordance with the adopted methodology (Poddaeva, 2022), at the first stage of the study, static tests are conducted to determine the aerodynamic coefficients. The obtained graphs of the dependence of lift force (C_y), drag force (C_x), and pitching moment (Cm_z) on the angle of attack of the flow at angles of attack (-10° to $+10^\circ$) for spans located in the wake are presented in Fig. 8.

In accordance with the methodology (Poddaeva, 2022), at the second stage of the study, dynamic tests of the aerodynamic stability of the superstructure model were conducted. The experimental studies

were performed at yaw angles of 0° and 180° , which correspond to the flow direction perpendicular to the axis of the superstructure — the most unfavourable from an aerodynamic point of view. During the dynamic tests, the model was mounted on spring suspensions in a specialised stand. The characteristics of the suspensions and their corresponding flow velocity scale were determined at the model design stage. The damping level of the model was measured and amounted to $\delta = 0.02$, which meets the requirements of GOST R 59625–2022. The low damping value is due to the rigid metal structure of the model and its

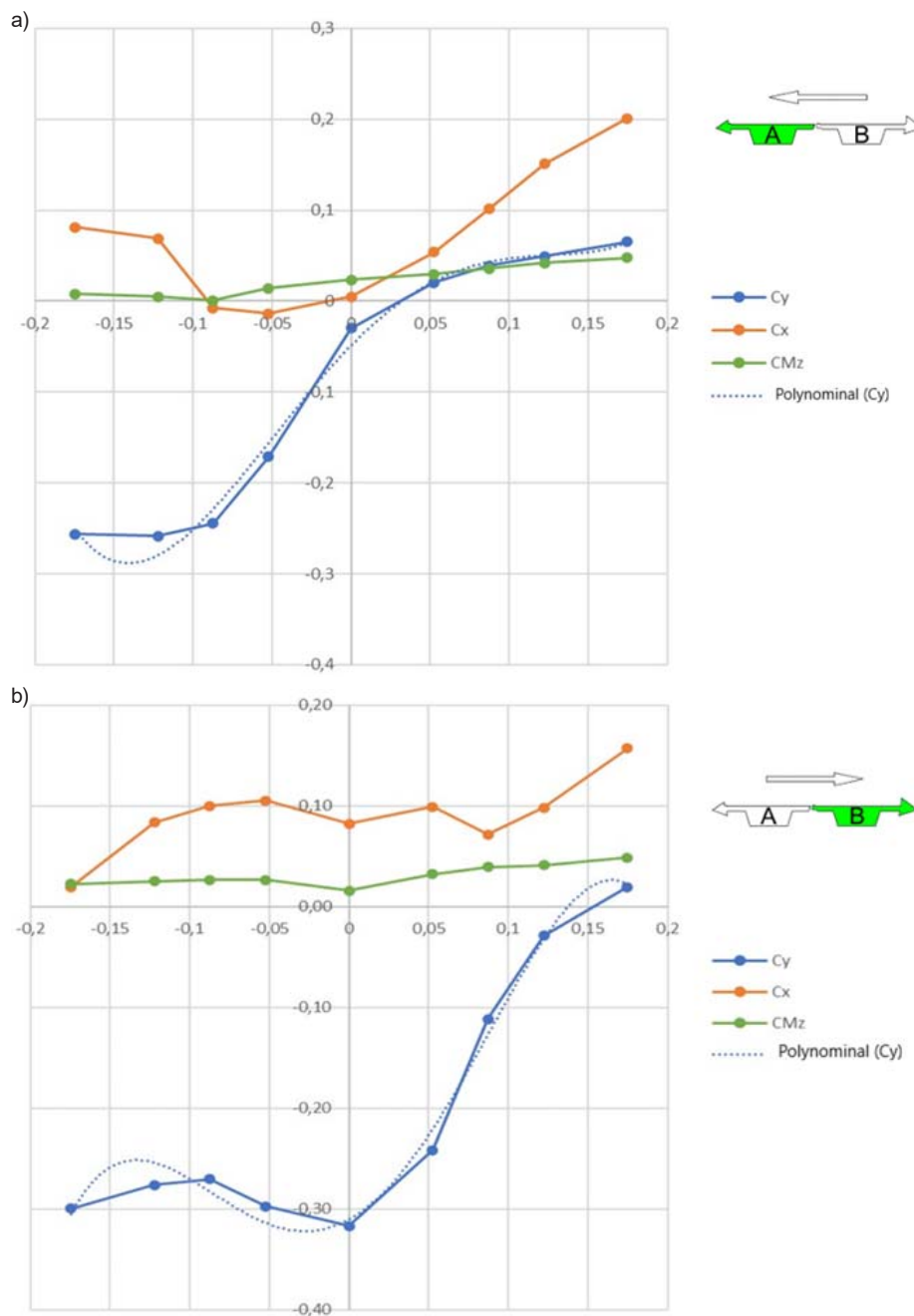


Fig. 8. Graphs of the dependence of lift force (C_y), drag force (C_x), and torsional moment (Cm_z) on the angle of attack of the flow at angles of attack (-10° to $+10^\circ$): (a) Model A in the wake of B; (b) Model B in the wake of A

low dissipative properties. To measure the model displacements, four optical sensors operating on the principle of laser triangulation were used. This method does not affect the free motion of the suspended model. The wind velocity was recorded using a Pitot tube connected to a high-sensitivity pressure sensor. The signals from the displacement sensors first passed through a low-pass filter and then were digitised by a 16-bit analogue-to-digital converter at a rate of 1,000 samples per second. Displacement measurements were taken relative to the zero level at a wind velocity of 0 m/s.

The stability assessment results are presented in the form of a graph of the full-scale superstructure displacement versus the mean wind velocity (Fig. 9). Vertical lines on the graph indicate threshold flow velocity values:

- design velocity — yellow line;
- critical flutter velocity — red line.

The critical flutter velocity value was calculated in accordance with the requirements of GOST R 59625–2022. The test programme provided for studies at yaw angles of 0° and 180° for angles of attack $\alpha = -5^\circ, -3^\circ, 0^\circ, +3^\circ, +5^\circ$.

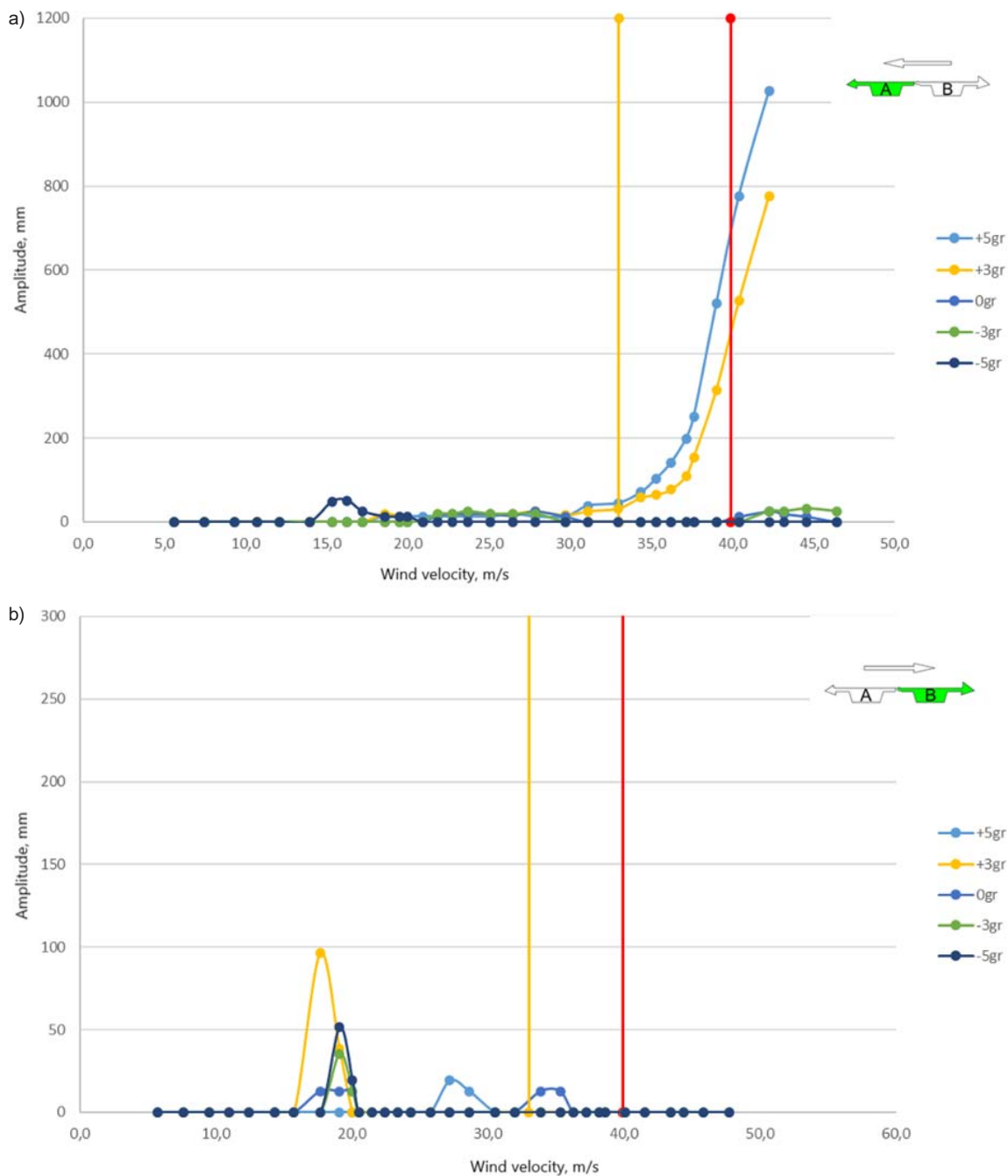


Fig. 9. Dependence of the oscillation amplitude A of the superstructure on the mean wind flow velocity at various angles of attack (bending oscillations in the first mode, yaw angle 180°): (a) Model A in the wake of B; (b) Model B in the wake of A

Table 4. Yaw angle 0° (Bridge B in the wake of A)

Angle of Attack	Phenomenon	Velocity Range (m/s)	Max. Amplitude (mm)
-5°	Vortex-induced excitation	19.1–20.0	51
-3°	Vortex-induced excitation	19.1–20.0	35
+3°	Vortex-induced excitation	17.7–19.1	96
+5°	Vortex-induced excitation	27.2–28.6	19

Table 5. Yaw angle 180° (Bridge A in the wake of B)

Angle of Attack	Phenomenon	Velocity Range (m/s)	Max. Amplitude (mm)	Special Conditions
-5°	Vortex-induced excitation	15.3–20.0	51 (at 16.3 m/s)	—
-3°	Vortex-induced excitation	22.0–28.0	26 (at 23.7 m/s)	—
0°	Vortex-induced excitation	22.0–30.0	26 (at 27.9 m/s)	—
+3°	Bending oscillations with amplitude growth	33.0–42.3	777 (at 42.3 m/s)	Beyond the calculated range for galloping; stopped for safety reasons
+5°	Bending oscillations with amplitude growth	33.0–42.3	1027 (at 42.3 m/s)	Beyond the calculated range for galloping; stopped for safety reasons

Results

During the experimental studies, various regimes of aeroelastic oscillations of bridge structures were identified (Tables 4, 5).

Conclusion and Discussion

As already mentioned, buffeting is one of the least studied phenomena of aerodynamic instability in building structures. Unlike other phenomena, such as galloping, divergence, and the similar-in-nature vortex-induced resonance excitation, there are currently no assessment methods for the analytical evaluation of buffeting occurrence. The only reliable way to assess the possibility of its occurrence is to conduct experimental studies. The conducted studies on section models have shown the occurrence of oscillations for one of the superstructures when it is located in the aerodynamic wake behind the other (Model B, leeward). Despite the fact that the shapes of the superstructures are almost identical,

their inclination relative to the oncoming flow, as well as the difference in the overall dimensions of the fairings, plays a significant role in the possibility of buffeting occurrence. This is precisely why, with the opposite orthogonal flow direction (Model A, leeward), buffeting is not observed. Thus, conducting experimental studies of the aerodynamic stability of twin parallel superstructures is of paramount importance in ensuring their reliability and mechanical safety, as it is currently the only way to identify the possibility of occurrence of such a dangerous phenomenon of aerodynamic instability as buffeting.

Funding

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ОЦЕНКА ВЛИЯНИЯ БАФТИНГА В СПУТНОМ СЛЕДЕ НА АЭРОДИНАМИЧЕСКУЮ УСТОЙЧИВОСТЬ МОСТОВ НА ОСНОВЕ ЭКСПЕРИМЕНТАЛЬНОГО МОДЕЛИРОВАНИЯ

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Аннотация

Введение. В статье рассматривается проблема аэродинамической устойчивости мостовых сооружений, в частности — явление бафтинга. Актуальность исследования обусловлена регулярными авариями и разрушениями мостов, среди причин которых — недоучёт ветровых воздействий и аэродинамическая неустойчивость конструкций. Целью работы является экспериментальная оценка аэродинамической устойчивости двухпролётного автодорожного моста (длина центрального пролёта — 130 м) с учётом возможного возникновения бафтинга. **Методика исследования включает:** изготовление физической модели пролётных строений с соблюдением геометрического и динамического подобия, проведение статических испытаний для определения аэродинамических коэффициентов, динамические испытания аэродинамической устойчивости модели. **Основные результаты:** Экспериментальные исследования на отсечных моделях показали, что бафтинг может возникать у пролётного строения, расположенного в аэродинамическом следе за другим, — при этом критическую роль играют наклон конструкции относительно набегающего потока и разница в габаритных размерах обтекателей. Экспериментальное моделирование в аэродинамических трубах остаётся ключевым методом оценки возможности/ невозможности возникновения явлений аэродинамической неустойчивости большепролетных мостов. Совершенствование расчётных моделей позволят снизить риски возникновения аварий мостовых конструкций, обусловленных ветровыми воздействиями.

Ключевые слова: бафтинг, экспериментальное моделирование, аэродинамические трубы, ветровые воздействия, аэродинамическая неустойчивость, мосты.

DAMPING OF TORSIONAL VIBRATIONS OF HIGH-RISE BUILDINGS UNDER SEISMIC EFFECTS USING DAMPERS GENERATING REACTIVE FORCE COUPLES

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Abstract

Introduction. To ensure the safety of buildings and structures in seismically active regions, special protection measures against destruction are applied. One of the most universal, effective, and economical methods of active vibration suppression is the method of reactive damping. An important form of natural vibrations of buildings is torsional motion. Certain segments of seismic accelerograms can provoke the development of such vibrations. There is a relationship between torsional and bending modes of vibration: bending vibrations can cause torsional deformations, and vice versa. This occurs because the centres of mass and the centres of stiffness of structural sections do not generally coincide, which leads to the occurrence of coupled bending-torsional vibrations. The aim of this work is to investigate the response of finite element (FE) models of high-rise buildings to seismic effects represented as harmonic functions with variable frequencies, varying the direction of the effect and the position of the centre of mass, as well as a comprehensive study of the results of experiments on damping torsional vibrations of high-rise buildings using a pair of reactive dampers capable of generating variable moments counteracting torsional vibrations. **Methods.** To evaluate the behaviour of high-rise buildings with reactive dampers under harmonic loads, an appropriate mathematical model was investigated. The calculations were performed using a software package based on the finite element method (FEM), and the dynamic response of the structure was determined numerically using the Newmark method. **Results.** The developed software tool allowed for frequency-vector analysis considering the displacement of the centre of mass from the centre of stiffness, and provided data on the torsional angles of the building at various positions of its centre of mass and variations in the parameters of the harmonic effect (frequency and direction) considering internal friction. A comprehensive study of the results of experiments on damping torsional vibrations of high-rise buildings using a pair of reactive dampers capable of generating variable moments counteracting torsional vibrations was conducted. It is shown that the use of reactive dampers with optimally selected parameters reduces the amplitude range of torsional vibrations by 50–80 %.

Keywords: high-rise buildings, seismic effect, oscillatory motion, centre of mass, torsional vibrations, reactive damper, vibration level.

Introduction

The issue of wind and seismic protection of high-rise buildings against destruction is extremely relevant. Within the framework of scientific research, an active search is underway for innovative, economically feasible, and relatively easy-to-implement solutions aimed at effective vibration damping and counteraction to dynamic loads.

Thus, Jung et al. (2024) analyse the seismic resistance of multi-storey reinforced concrete frames infilled with precast modular blocks. As a solution to the identified problems of traditional seismic strengthening methods (for frames with transverse, stone walls and precast panels), a new concept is proposed — the use of precast modular block walls. The study by Tan et al. (2023) is devoted to assessing the effect of wind loads on seismically isolated high-rise structures developed using an integrated seismic protection design approach.

This method is based on the theory of complex response spectrum and complex complete quadratic combination. The study by Wang et al. (2024) examines how various types of dampers (inerters and negative stiffness) installed on outriggers of high-rise buildings affect vibration damping. Special attention is paid to considering soil-structure interaction. The development and verification of an innovative hybrid damper designed to combat vibrations of high-rise buildings is presented in research by Lai et al. (2024). This damper utilises velocity-squared damping. It was successfully modelled numerically and confirmed by experiments. The works (Shein et al., 2023; Shein et al., 2025) contain numerical confirmation of the effectiveness of a reactive damper for reducing rectilinear seismic vibrations of tower structures and high-rise buildings. The results demonstrate a high level of damping, which allows, when using a damping device with carefully

calculated characteristics, to ensure a reduction in the amplitude range of rectilinear mechanical vibrations of structures by 50–80 %, thereby confirming its practical value.

Regulatory documents require that in areas of increased seismic activity, symmetrical in plan (geometric and stiffness) structural solutions for buildings and structures should be adopted.

However, even in buildings with an ideal architectural and planning solution, the torsion effect is observed, because the random eccentricity between the centres of mass and stiffness causes rotation of the floors, even with rectilinear motion of the base (Botis and Cerbu, 2020; Hussein, 2019). This rotation overloads the perimeter columns and external walls. Analysis of the consequences of earthquakes has revealed frequent destruction of the end parts of buildings (Bondarev, 2017). The unevenness of torsion increases the risk of building destruction under strong dynamic effects, therefore, there is a need to apply special protection measures (Zhang et al., 2025; Calvi et al., 2026). The aim of this work is to develop and evaluate an innovative approach to damping torsional vibrations of high-rise buildings during seismic activity using reactive systems that generate pairs of gas jets with a high ejection velocity. These systems create alternating force couples at specified time intervals, which counteract torsional deformations and torsional vibrations of the high-rise building that occur under non-stationary seismic loads.

Subject, Tasks and Methods

Within the framework of this study, the functioning of reactive damper systems designed to damp vibrations of a high-rise building under seismic loads was investigated. The building, having a rectangular base with dimensions of 42×18 m and a height of 150 m (corresponding to 50 storeys), has a frame-core structural scheme with a central rigid core. Detailed stiffness and geometric parameters of the reinforced concrete frame elements are given in Table 1.

The detailing of the reinforcement of the structural elements of the building is shown in Fig. 1c.

The displacements of the centre of mass (CM) of the high-rise building along the coordinate axes OX and OY were modelled by changing the specific weight of the finite elements of the model located at the perimeter.

The seismic effect was modelled by an accelerogram in the form of a harmonic function:

$$f = A \sin(pt), \quad (1)$$

where $A = 5 \text{ m/s}^2$ is the amplitude of the translational acceleration (const), p is variable frequency of the disturbing effects.

The research work is based on the software package “Fluctuations”, developed in the MatLab environment. The main equation adopted in the software package and describing the dynamics of plate-rod systems using the finite element method (FEM) has the form:

$$M\ddot{U} + C\dot{U} + KU = P, \quad (2)$$

where M , C and K are the matrices of masses, internal friction (damping) and stiffness corresponding to the finite element discretisation of the system, P is the column vector of external forces (seismic load).

This package provides a numerical solution to the system of differential equations (2).

For modelling the columns of the high-rise building, bar finite elements with 6 degrees of freedom in each node are used (three linear displacements along the coordinate axes of the global coordinate system and three angles of rotation around these axes). For modelling floor and roof slabs, rectangular thin plate finite elements are used, possessing 3 degrees of freedom in the node: one linear displacement along the normal to the element plane and two angles of rotation around its local coordinate axes.

The calculation of the internal friction matrix C is carried out according to the following relationship:

$$C = \alpha \cdot M + \beta \cdot K, \quad (3)$$

To calculate the constants α and β of Equation (3), it is necessary to determine the two lowest frequencies of the natural vibration frequency spectrum of the building under consideration. These values were determined using a separate block of the “Fluctuations” software, which solves the system of equations describing the free vibrations of the finite element model of the building under study:

$$\left| M^{-1}K - \omega^2 E \right| = 0, \quad (4)$$

where ω is an element of the natural vibration frequency spectrum.

The seismic load was specified based on the modification of the linear translational movements of the base of the building under consideration into the force effect on it. The direction of the seismic load in

Table 1. Stiffness and geometric parameters of the reinforced concrete frame elements

Element	Dimensions	Concrete Class	Reinforcement
1. Rigid core	6000 x 6000 mm, wall thickness $t_{\text{wall}} = 250 \text{ mm}$	Heavy, B35	Steel mesh Ø12 A400, spacing – 200 mm
2. Columns	700 x 700 mm – lower part of the building (1/2 of height), 500 x 500 mm – upper part	Heavy, B35	Ø32 A400, spacing – 100 mm (working)
3. Slabs	$t = 200 \text{ mm}$	Heavy, B35	Steel mesh Ø10 A400, spacing – 200 mm

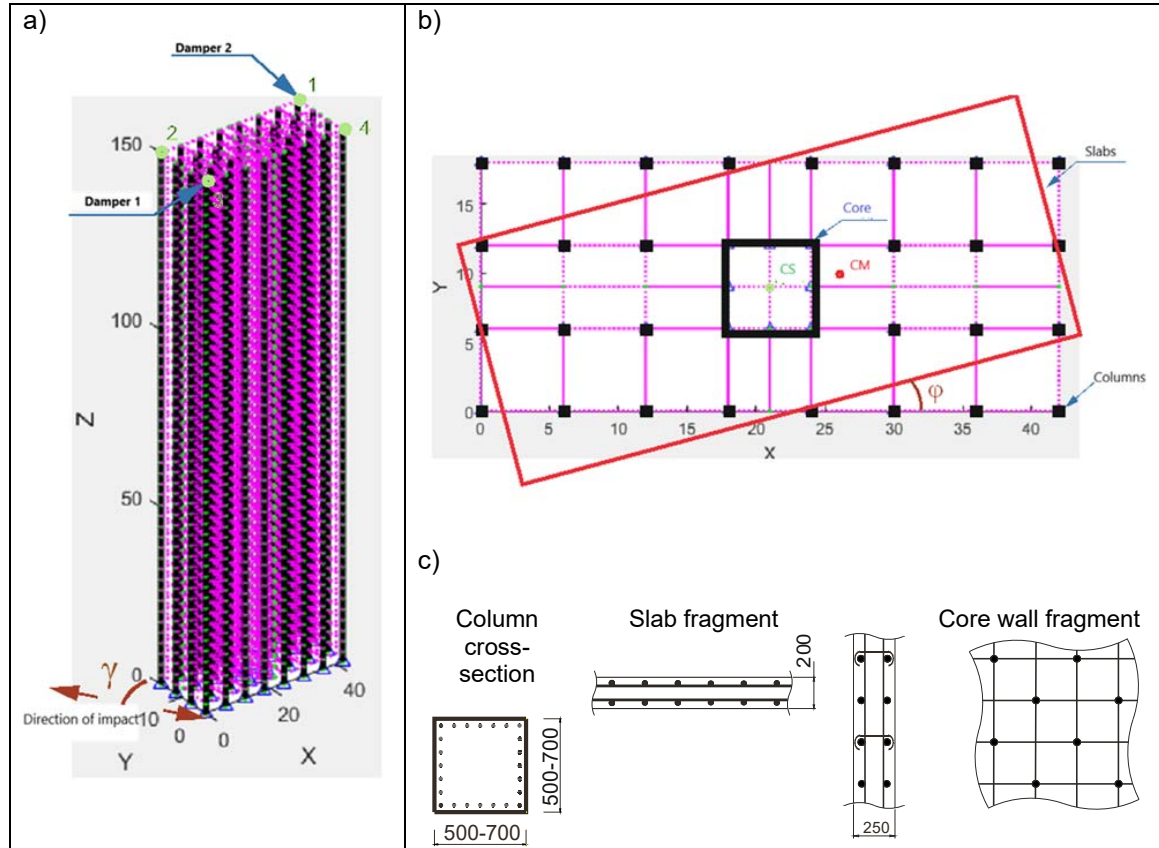


Fig. 1. Design scheme of the building: (a) modelling of the design scheme in the software package; (b) location of structural elements; (c) schemes detailing the reinforcement of various building structures

the horizontal plane OXY depended on the value of the angle θ with the OY axis of the general reference system (Fig. 1a).

To reduce the amplitude of torsional vibrations, the principle of operation of vibration dampers was used (Shein et al., 2025): alternating-sign reactive forces creating a reactive couple are generated by gas jets escaping from nozzle openings under high pressure.

In the proposed studies, the dampers were located in two nodes of the finite element model of the building (Fig. 1a), located at opposite ends of the diagonal. The mutually opposite reactive forces from the dampers, creating a reactive couple, were directed orthogonally to this diagonal.

The dampers were activated when the controlled angle of rotation of the roof around the vertical axis of symmetry passing through the centre of stiffness (CS) (Fig. 1b) reached a specified value $\varphi_{\max}$. The direction of the reactive forces of the dampers was determined by the direction of the velocity vectors of the nodes in which they were located, i.e., opposite to them.

The reactive force arising from the combustion of the fuel mixture is represented by a known function of the form:

$$R = V_e \cdot \frac{dm}{dt}. \quad (5)$$

where V_e is the exhaust velocity of the combustion products, $\dot{m}$ is the rate of change of its mass.

The equation of motion of a finite element node of the design model of the building under study, considering the effects of the reactive force of the damper on it, takes the form:

$$(M_i + m_i)\ddot{u}_i + \sum_{j=1}^n c_{ij}\dot{u}_j + \sum_{j=1}^n k_{ij}u_j = P_i \mp v_e \cdot \dot{m}_i, \quad (6)$$

where m_i is the variable mass of the damper, the diagonal mass matrix:

$$M = \text{diag}[M_1 \ M_2 \ \dots \ M_i + m_{i,t+\Delta t} \ \dots \ M_n], \quad (7)$$

and the column vector of external forces:

$$P = [P_1 \ P_2 \ \dots \ P_i \mp V_e(m_{i,t+\Delta t} - m_{i,t}) / (\Delta t) \ \dots \ P_n]^T. \quad (8)$$

The optimal result of vibration damping is determined by the following key damper parameters:

- exhaust velocity of fuel combustion products (reactive jet) — V_{gas} , m/s,
- time of one cycle of its exhaust — T_{gas} , s,
- maximum permissible value of the angle of rotation of the roof around the vertical axis of symmetry of the protected mechanical system — $\varphi_{\max}$, rad.

The study investigated how the change in the position of the centre of mass affects the torsional

angle of the high-rise building at various directions of seismic effect and various natural vibration frequencies, as well as how the main damper parameters affect the effectiveness of damping torsional vibrations of the building under study.

Results and Discussion

1. Analysis of frequencies and modes of vibration of the high-rise building at various positions of its centre of mass

Using the software package, a frequency analysis of the building was performed depending on the displacement of the centre of mass from the centre of stiffness. The mosaics of the first three natural frequencies, depending on the CM displacement, are shown in Fig. 2.

The characteristic first three natural vibration modes are shown in Fig. 3.

The results obtained show that when the CM is displaced, no significant changes in the values of natural vibration frequencies occur; however, the fundamental mode shapes become bending-torsional.

2. Analysis of torsional angles of the high-rise building at various positions of its centre of mass and changes in the parameters (frequency and direction) of the harmonic effect

Figs. 4–6 show graphs of the torsional angles of the roof slab depending on the displacement of the centre of mass from the centre of stiffness along the coordinate axes OX (X_{cw}) and OY (Y_{cw}).

3. Damping of torsional vibrations using dampers generating reactive couples

Within the framework of this analysis, we proceed from the assumption of the constancy of the gas exhaust velocity from the damper nozzle:

$$V_e = \text{const}, \quad (9)$$

The change in the mass of the fuel fluid is modelled by a decreasing function:

$$m = m_0(1 - \beta t), \quad (10)$$

where β — const [c^{-1}].

The shape of the pulses from the reactive dampers is assumed to be rectangular (sudden application) (Fig. 7).

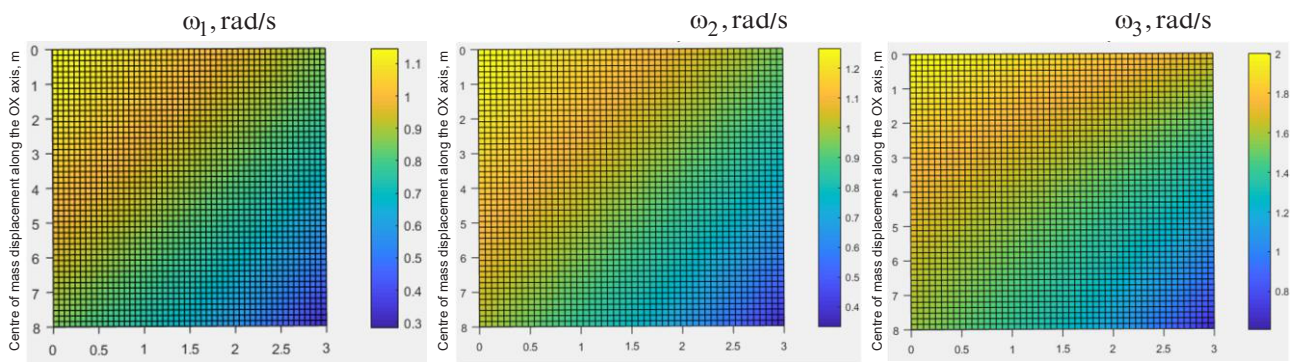


Fig. 2. Frequency mosaics

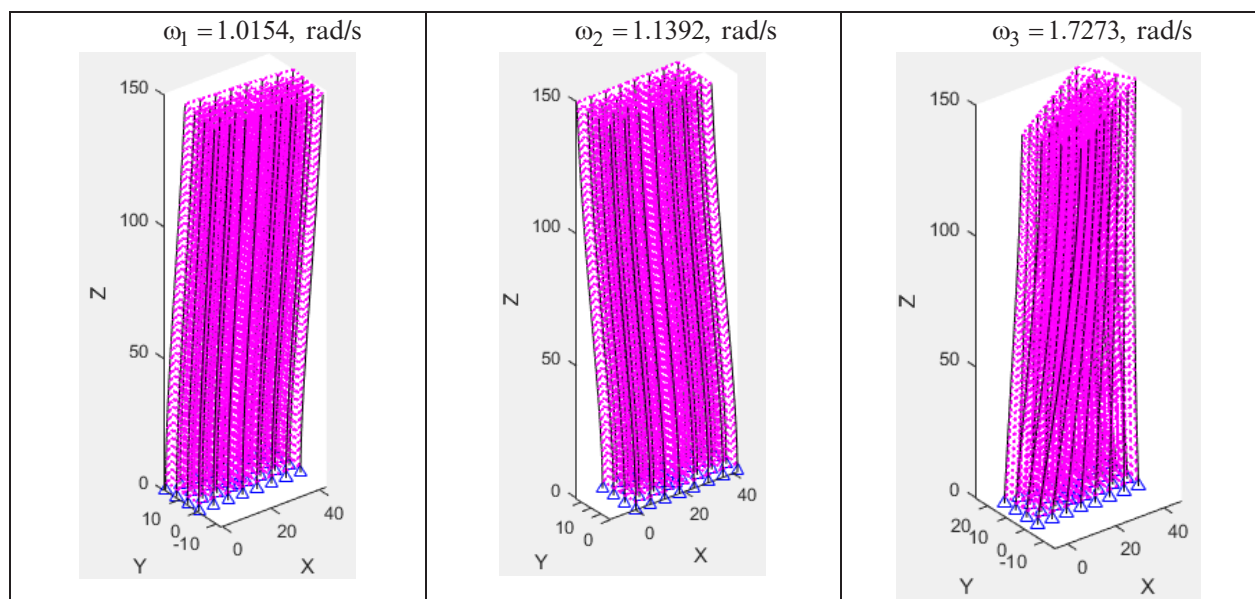


Fig. 3. Vibration modes

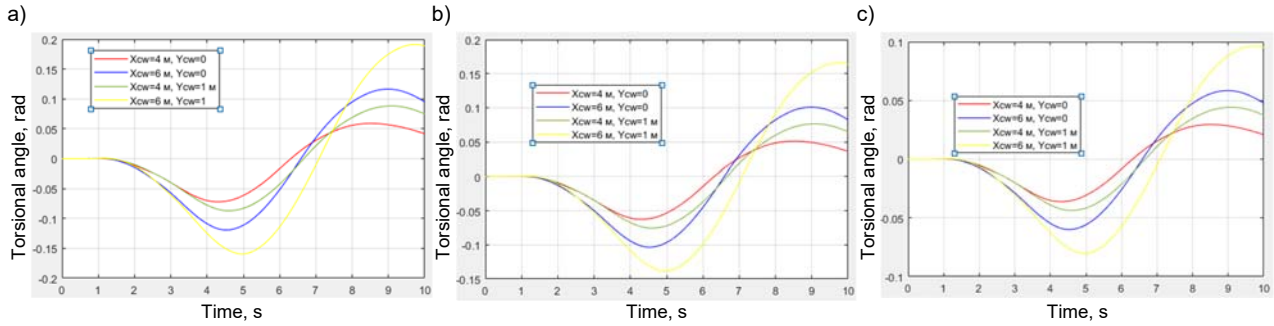


Fig. 4. Torsional angles of the building φ at the disturbing effect frequency $p = 0.5$ rad/s: a) $\gamma = 0^\circ$, b) $\gamma = 30^\circ$, c) $\gamma = 60^\circ$

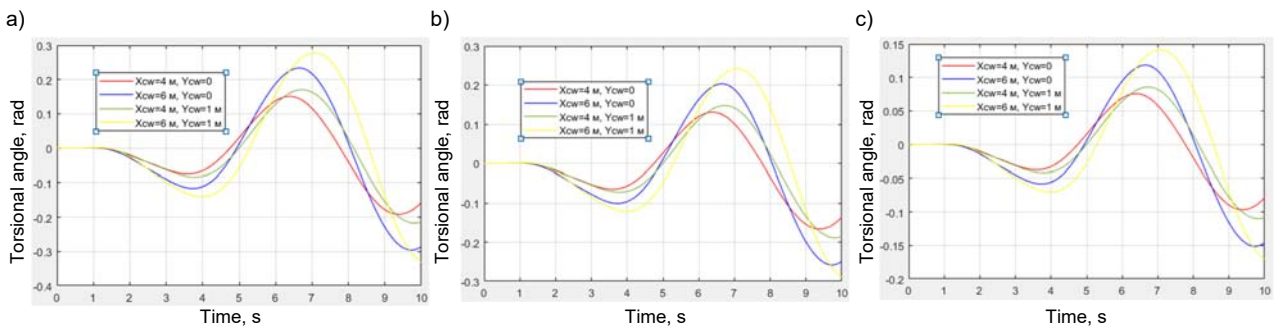


Fig. 5. Torsional angles of the building φ at the disturbing effect frequency $p = 1$ rad/s: a) $\gamma = 0^\circ$, b) $\gamma = 30^\circ$, c) $\gamma = 60^\circ$

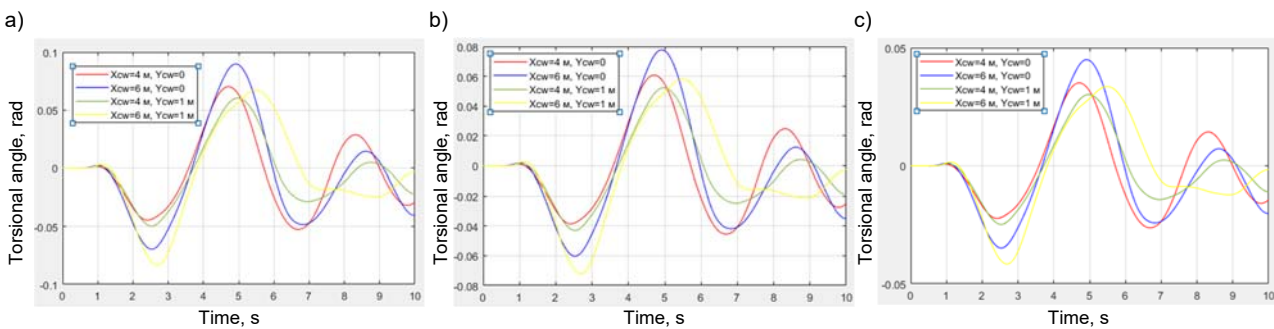


Fig. 6. Torsional angles of the building φ at the disturbing effect frequency $p = 2$ rad/s: a) $\gamma = 0^\circ$, b) $\gamma = 30^\circ$, c) $\gamma = 60^\circ$

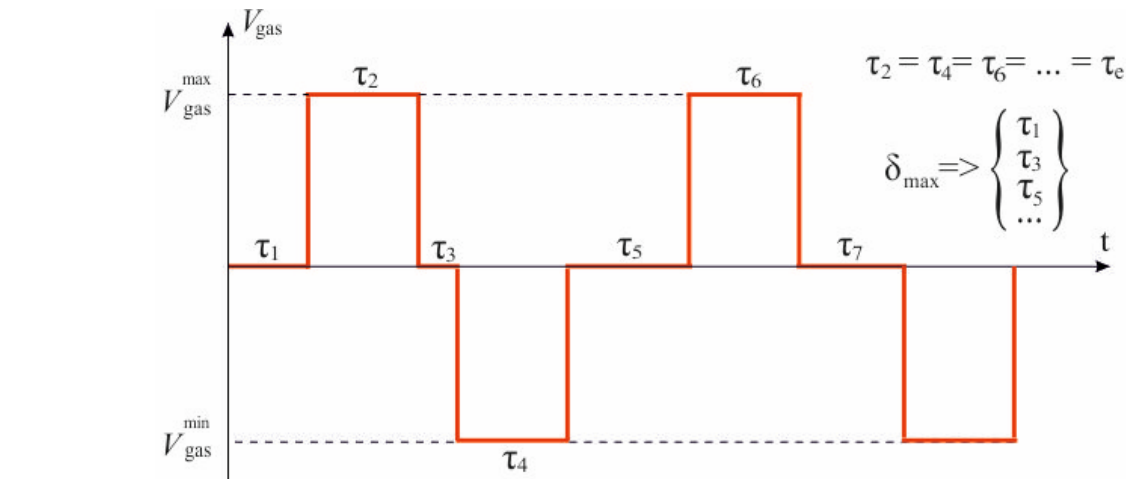


Fig. 7. Dependence of the jet velocity V_{gas} on time

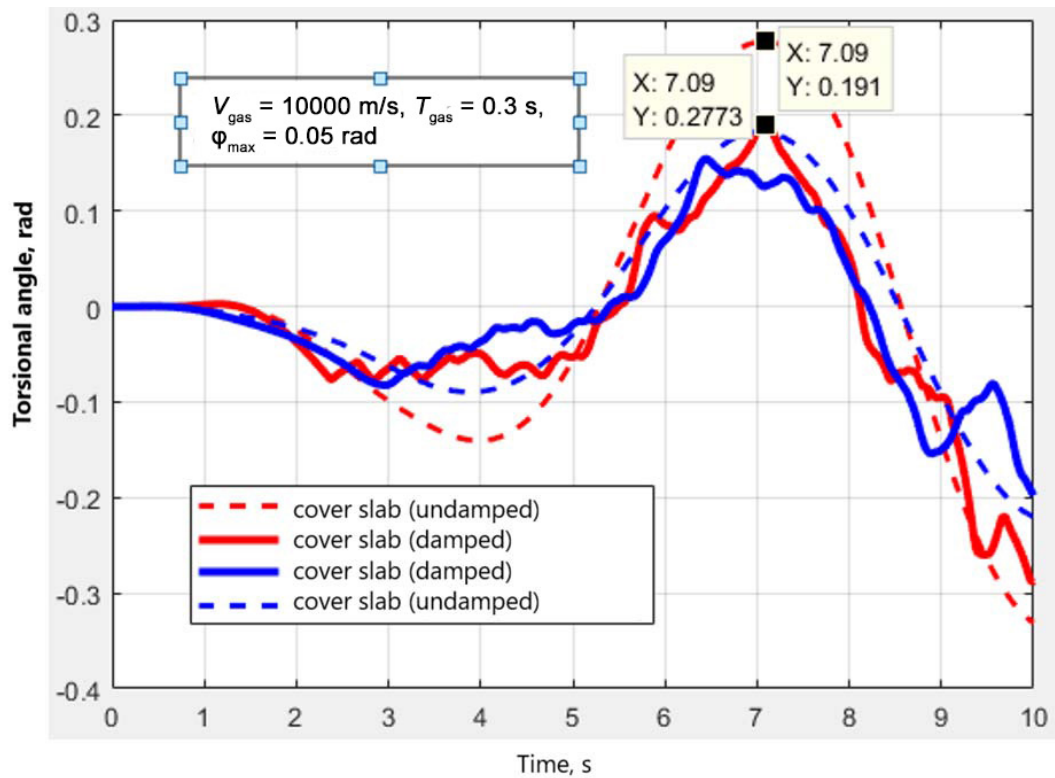


Fig. 8. Torsional angles of slabs

The efficiency of the damper system was assessed based on the analysis of the torsional angles of the roof slab and the floor slab located in the middle of the building height.

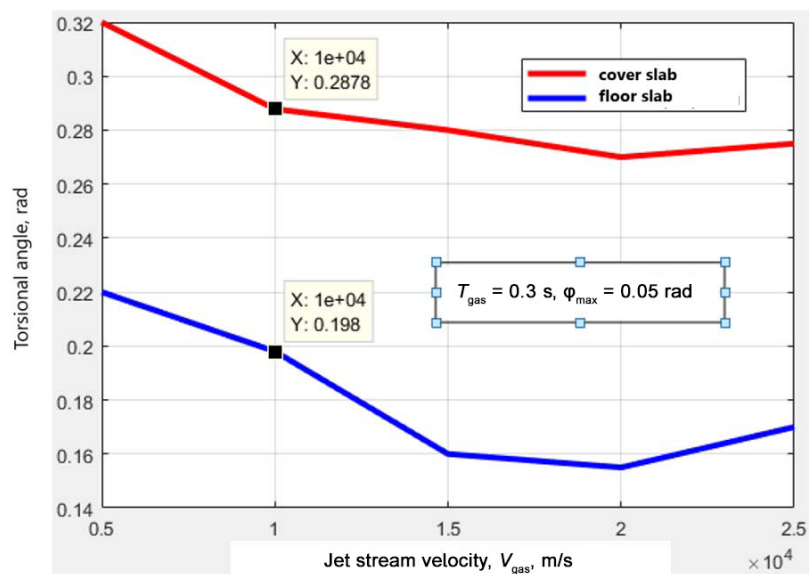
The results obtained at the selected values in the first approximation: $V_{\text{gas}} = 10000 \text{ m/s}$, $T_{\text{gas}} = 0.3 \text{ s}$, $\varphi_{\text{max}} = 0.05 \text{ rad}$, are shown in Fig. 8.

The maximum torsional angles of slabs in the form of functional dependences on the main damper

characteristics V_{gas} , T_{gas} , φ_{max} are shown in the following graphs (Figs. 9–11).

4. Optimisation of the main characteristics of reactive dampers

Using the developed software package, a tabular dependence of the maximum torsional angle of the floor slab on the velocity V_{gas} and time T_{gas} of the reactive jet exhaust of the dampers was constructed. Using the module of the developed software package

Fig. 9. Maximum torsional angles of slabs as functions of V_{gas} functions of angle φ_{max}

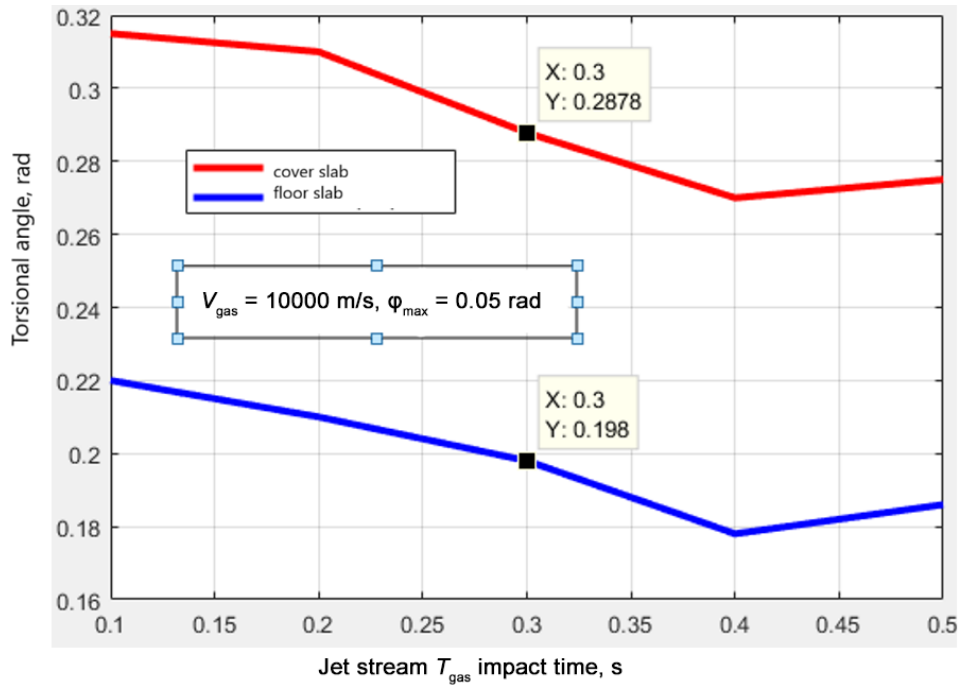


Fig. 10. Maximum torsional angles of slabs as functions of T_{gas}

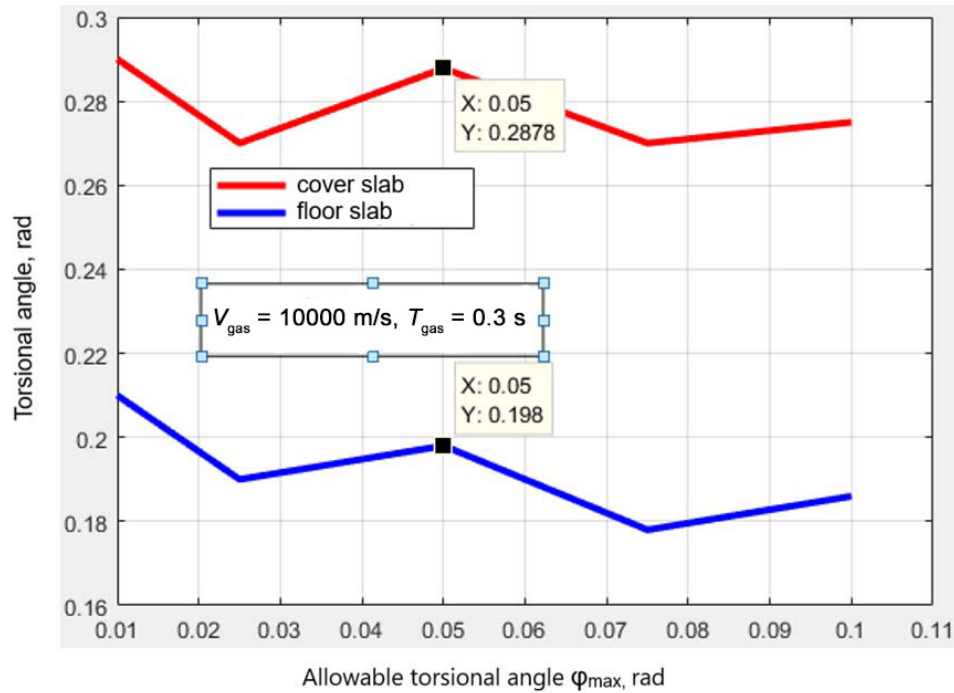


Fig. 11. Maximum torsional angles of slabs as functions of angle ϕ_{max}

for solving optimisation problems, the objective function of the form was minimised (Fig. 12):

$$U_{max}(V_{gas}, T_{gas}) \rightarrow \min.$$

Fig. 13 shows the local minimum of the function of two variables found using the software tool.

The optimal damper characteristics for this task, obtained by calculation: $V_{gas} = 17000$ m/s, $T_{gas} = 0.08$ s (Fig. 14).

Conclusions

The influence of the eccentricity between the CM and the CS on the torsional vibrations of the floors of high-rise buildings around the centre of mass has been investigated. A mathematical model of a high-rise building equipped with dampers generating reactive force couples counteracting torsion has been developed. Numerical testing

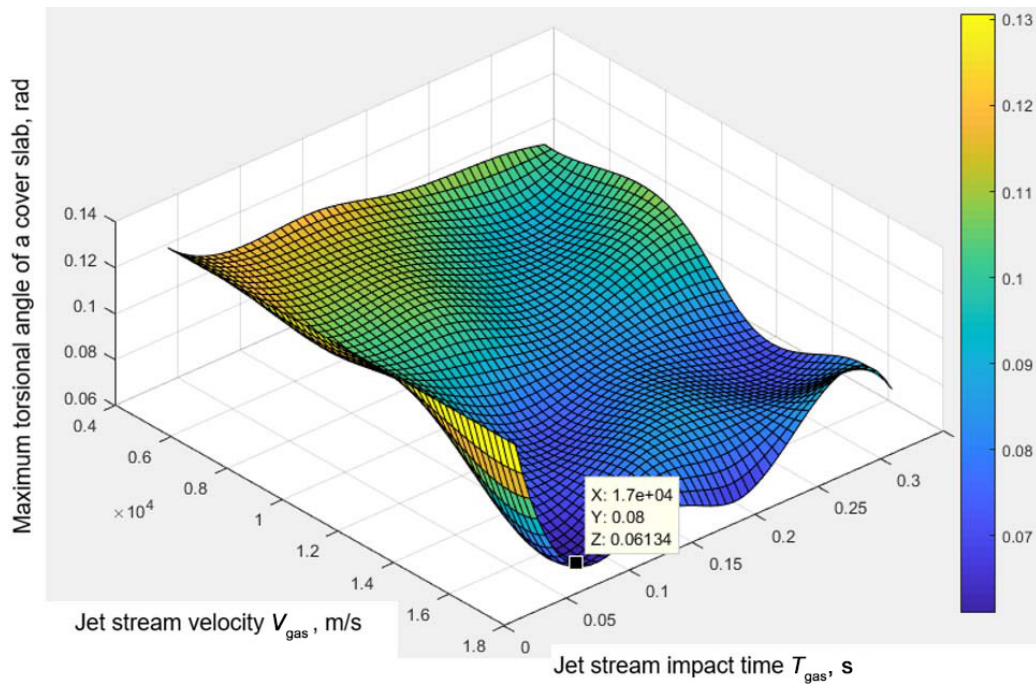


Fig. 12. Analytical function of the torsional angle of the floor slab

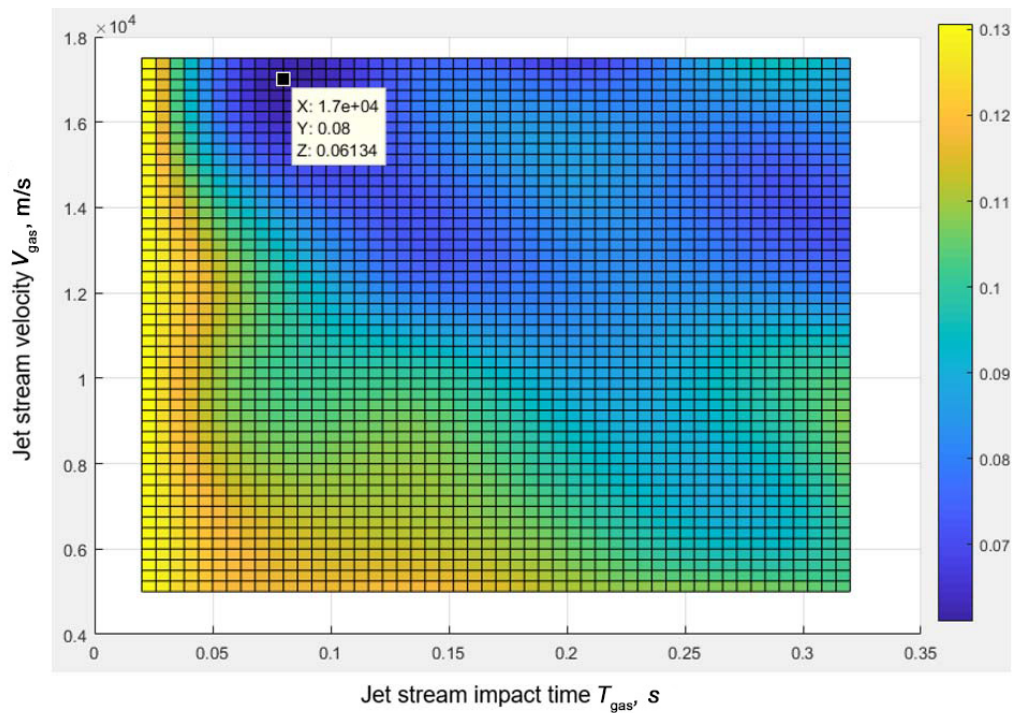


Fig. 13. Maximum torsional angles of the floor slab with local minimum

of the technical means, mathematical model and programme in the MATLAB environment for damping torsional vibrations has been carried out. The evaluation of the performance of the dampers, as well as the selection, tuning and optimisation of their parameters, was carried out based on the results of the analysis of numerical experiments. It is shown that reactive damping of torsional

vibrations can provide increased survivability of high-rise buildings, reducing the level of torsional vibrations by 50–80 %.

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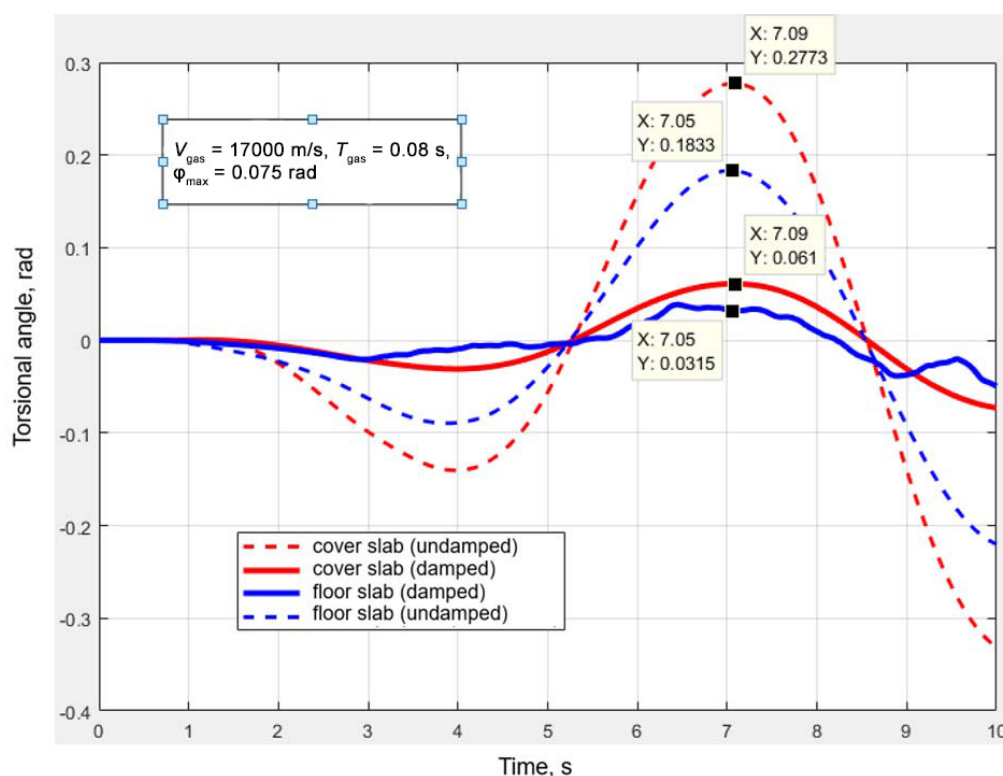


Fig. 14. Torsional angles of slabs at the found optimal damper characteristics

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ГАШЕНИЕ КРУТИЛЬНЫХ КОЛЕБАНИЙ ВЫСОТНЫХ ЗДАНИЙ ПРИ СЕЙСМИЧЕСКИХ ВОЗДЕЙСТВИЯХ С ИСПОЛЬЗОВАНИЕМ ДЕМПФЕРОВ, СОЗДАЮЩИХ РЕАКТИВНЫЕ ПАРЫ СИЛ

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Аннотация

Введение. Для обеспечения безопасности зданий и сооружений в сейсмически активных районах применяются специальные меры защиты от разрушений. Одним из наиболее универсальных, действенных и экономичных методов активного подавления колебаний является способ реактивного демпфирования. Важной формой собственных колебаний зданий являются крутильные движения. Определенные участки сейсмических акселерограмм могут провоцировать развитие таких колебаний. Между крутильными и изгибными формами колебаний существует взаимосвязь: изгибные колебания могут вызывать крутильные деформации, и наоборот. Это происходит из-за того, что центры масс и центры жесткости сечений сооружений в общем случае не совпадают, что приводит к возникновению комбинированных изгибно-крутильных колебаний. Целью данной работы является исследование реакции конечно-элементных (КЭ) моделей высотных зданий на сейсмические воздействия, представленные в виде гармонических функций с переменными частотами при варьировании направления воздействия и положения центра масс, а также всестороннее изучение результатов экспериментов по гашению крутильных колебаний высотных зданий с использованием пары реактивных демпферов, способных генерировать переменные моменты, противодействующие торсионным колебаниям. **Методы.** Для оценки поведения высотных зданий с реактивными демпферами при гармонических нагрузках была исследована соответствующая математическая модель. Расчеты проводились с использованием программного комплекса на основе метода конечных элементов (МКЭ), а динамический отклик конструкции определялся численно методом Ньюмарка. **Результаты.** Разработанное программное средство позволило провести частотно-векторный анализ, учитывающий смещение центра масс от центра жесткости, и получить данные об углах закручивания здания при различных положениях его центра масс и вариациях параметров гармонического воздействия (частоты и направления) с учетом внутреннего трения. Проведено всестороннее изучение результатов экспериментов по гашению крутильных колебаний высотных зданий с использованием пары реактивных демпферов, способных генерировать переменные моменты, противодействующие торсионным колебаниям. Показано, что применение реактивных демпферов с оптимально подобранными параметрами снижает размах амплитуд крутильных колебаний на 50–80 %.

Ключевые слова: высотное здание, сейсмическое воздействие, колебательное движение, центр масс, крутильные колебания, реактивный демпфер, уровень колебаний.

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