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Original Research Article

Geotechnical solutions for urban centers: Bridging engineering innovations with socio-economic development

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ABSTRACT

In the face of mounting geotechnical challenges within urban centers worldwide, the significance of engineering solutions extends beyond the immediate resolution of these issues to act as catalysts for socio-economic development. This paper examines specific geotechnical problems, such as soil instability and the underutilization of urban green spaces, and their direct impact on community health, safety, and the quality of urban life. With a focus on diverse international case studies, the research clarifies the reciprocal influence between geotechnical innovation and socio-economic advancements. It advocates for the integration of geotechnical practices into the broader scope of urban planning, detailing how cities can leverage these practices for sustainable growth and enhanced community well-being.

Keywords: geotechnical engineering; urban development; socio-economic growth; sustainable solutions; infrastructure; urban challenges; green spaces; seismic activities

1. Introduction

The intricate fabric of modern urbanization is transforming rapidly, with more than half of the world's population now residing in cities—a figure expected to rise to 68% by 2050[1]. These urban expanses are a complex blend of architecture, technology, and human networks. Under this veneer lies the critical role of geotechnical engineering—a key yet often overlooked driver of urban development. It provides foundational stability and safety, influencing the socio-economic fabric of cities. As urban areas burgeon, the specific challenges posed by diverse geological conditions, including varying soil compositions and environmental pressures, call for tailored geotechnical interventions. Yet the essence of sustainable urban growth goes beyond engineering solutions. This study seeks to articulate the precise problem of how geotechnical approaches can be harmoniously woven into the socio-economic context of urban expansion, ensuring that technological advancements in geotechnical engineering are not siloed but are part of a cohesive strategy for urban prosperity.

2. Methodology

The methodology employed in this study is designed to provide a comprehensive understanding of the geotechnical challenges and innovations within urban centers and their socio-economic implications. Our

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approach is threefold, encompassing a systematic literature review, empirical data collection, and a comparative case study analysis.

Systematic literature review: To ensure a thorough investigation, we conducted an extensive literature review, drawing from a wide array of sources, including peer-reviewed journals, industry reports, and global urban development databases. The literature was meticulously selected based on relevance to geotechnical engineering, urban development, and socio-economic outcomes, with a particular focus on works published in the last two decades. This review provided the foundational knowledge necessary to identify the pivotal geotechnical challenges and innovations impacting urban environments.

Empirical data collection: Our empirical data were sourced from a combination of academic databases, urban planning archives, and direct correspondence with municipal engineering departments. This multi-source strategy enabled the acquisition of robust and diverse data sets, including geotechnical assessments, economic reports, and urban planning documents. The data spans a wide geographic and developmental spectrum, ensuring a balanced view of geotechnical engineering's role in various urban contexts.

Comparative case study analysis: The core of our research lies in the comparative case studies, which were selected through a criterion-based sampling method. Criteria included the scale of urban development, the intensity of geotechnical challenges, and the level of innovation in geotechnical solutions. Each case study was analyzed in terms of its approach to geotechnical engineering, the socio-economic context, and the outcomes achieved. The comparative nature of this analysis allowed us to identify patterns and draw broader insights into the efficacy of geotechnical solutions in driving socio-economic development.

Analytical framework: The analysis was structured around a bespoke framework that considers both engineering and socio-economic dimensions. This dual-focus framework facilitated a nuanced analysis of how geotechnical engineering not only solves structural issues but also contributes to economic growth, community well-being, and social equity. Statistical tools and qualitative assessments were employed to evaluate the impact of geotechnical solutions and derive conclusions that are both scientifically rigorous and socio-economically relevant.

Through this multi-dimensional methodology, the study ensures that the conclusions drawn are well-grounded in empirical evidence and reflective of the complex interplay between geotechnical engineering and urban socio-economic dynamics.

3. Historical context of geotechnical failures and urban planning

Historically, urban settlement was driven by necessity. Civilizations such as the Indus Valley thrived near water sources without a comprehensive understanding of the underlying geotechnics, leading to their decline when natural changes occurred[2]. The 20th century witnessed the repercussions of neglecting geotechnical factors, exemplified by the Leaning Tower of Pisa's foundational miscalculations[3]. The socio-economic impacts of these failures—economic losses, population displacements, and heritage degradation—demonstrate the severe consequences of geotechnical oversight.

Learning from past mistakes, this paper investigates how historical geotechnical failures have shaped contemporary urban planning. The 1906 San Francisco earthquake serves as a pivotal case where the reconstruction efforts incorporated advanced geotechnical understanding, signifying a paradigm shift in urban redevelopment[4]. Despite this progress, socio-economic inequality, exacerbated by geotechnical inadequacies, persists, underscoring the urgent need to address this disparity. The paper aims to bridge this gap, offering comprehensive insights into how geotechnical engineering can be effectively integrated with socio-economic objectives to foster equitable and resilient urban development.

4. Geotechnical challenges in modern urban landscapes

The transformation of urban landscapes in the 21st century has been profound, with geotechnical engineering at the forefront of this evolution. The challenge lies in accommodating the vertical aspirations of megacities while ensuring the stability of their foundations. In cities such as Dubai and Shanghai, the construction of skyscrapers is a marvel of modern engineering, grappling with the complexities of building on unstable desert terrain and river deltas[5]. This section aims to dissect these complexities, detailing the intricate strategies employed to overcome the geotechnical challenges of skyscraper construction.

Moreover, the socio-economic ramifications of these geotechnical feats are significant. In Dubai, for example, the geotechnical intricacies involved in erecting its iconic skyline required a substantial financial outlay. This investment not only propelled the structural development but also had a multiplier effect, invigorating the city's real estate market and bolstering its tourism industry[6]. The empirical data presented will underscore the economic benefits that stem from geotechnical advancements, substantiating the argument with a quantitative analysis of investment flows and sectoral growth rates.

Conversely, the geotechnical challenges faced by smaller urban entities, though different in scale, are no less critical. Suburban sprawl often neglects geotechnical assessments, leading to residential and infrastructure challenges. For instance, the prevalence of differential settlement in residential areas can impose unforeseen economic strains on homeowners as well as pose risks to structural integrity[7]. This article will expand on these suburban geotechnical challenges by incorporating a comparative analysis of soil testing policies and their economic impact on suburban homeowners.

The empirical breadth of the paper will be enhanced by examining a broader array of urban environments, both megacities and smaller municipalities. This comparative study will provide a granular view of how geotechnical challenges manifest across different urban scales and their consequent socio-economic effects. It will also emphasize the necessity of adaptive geotechnical solutions that are sensitive to the socio-economic fabric of urban centers, regardless of their size.

5. Case studies: Geotechnical interventions and socio-economic turnarounds

This section presents an array of case studies that exemplify the transformative power of geotechnical interventions in urban settings. Spanning across various continents and urban scales, these studies illuminate the intricate relationship between geotechnical solutions and socio-economic development. Each case study was selected for its demonstrative value in showing how geotechnical challenges were converted into opportunities that spurred economic growth, enhanced public safety, and improved quality of life.

5.1. The reinforcement of Tokyo's waterfront

Geotechnical challenge: Tokyo's waterfront, particularly in areas like Odaiba, was constructed on reclaimed land, which is highly susceptible to liquefaction during seismic events. The devastating 2011 Tohoku earthquake and tsunami highlighted the risks associated with such geotechnical conditions, presenting a crucial problem for the city's infrastructure and safety.

Intervention strategy: The Tokyo Metropolitan Government initiated a comprehensive reinforcement project, which included the use of deep soil mixing and the installation of subterranean walls to prevent liquefaction. The waterfront buildings were also equipped with advanced anti-seismic technologies, such as base isolation systems, to reduce the transmission of seismic forces to the structures.

Socio-economic impact: The reinforcement of Tokyo's waterfront has had extensive economic and social benefits. The area has seen a marked increase in real estate development, a surge in tourism, and an improvement in public confidence in infrastructure safety. Moreover, the implementation of these engineering solutions has served as a benchmark for other seismic-prone cities globally.

Data and metrics: The success of these interventions is evident in the enhanced safety measures, where post-implementation assessments show a significant reduction in potential damage from future seismic events. Economic indicators reflect a 30% rise in property values in the waterfront area and a 20% increase in tourism revenue since the completion of the reinforcement project[8–10].

5.2. Subway expansion in Seoul

Geotechnical challenge: Seoul's rapid urbanization brought significant challenges, including traffic congestion and the need for efficient public transport solutions that could navigate through the city's dense urban fabric and varied geotechnical conditions, such as the soft sediments of the Han River's floodplain.

Intervention strategy: The Seoul Metropolitan Government embarked on an ambitious expansion of its subway system. This included the adoption of cutting-edge tunneling techniques and the extensive use of shield machines that allowed for deep underground construction without disrupting surface activities. The designs incorporated comprehensive geotechnical risk assessments to ensure the long-term stability of the subway tunnels.

Socio-economic impact: The expansion of the subway system has been a catalyst for Seoul's economic growth, improving accessibility and reducing the reliance on private vehicles. This has not only mitigated air pollution but also contributed to a surge in the development of businesses and residential areas around new subway stations. The initiative has enhanced Seoul's reputation as a leader in sustainable urban transportation, which has further attracted international investment and talent.

Data and metrics: Since the expansion, there has been a reported 15% decrease in traffic congestion and a 25% increase in public transport usage. The areas surrounding new subway lines have seen a 20% increase in property values and a comparable rise in new business registrations, indicating a positive economic impact[11,12].

5.3. Slope stabilization in Rio de Janeiro

Geotechnical challenge: The steep slopes of Rio de Janeiro's favelas have historically been prone to landslides, particularly during the rainy season. The dense, unplanned construction in these areas exacerbated the risks, with many homes built on unstable ground without proper foundations, posing a threat to life and property.

Intervention strategy: The city implemented a comprehensive slope stabilization program. This involved constructing retaining walls, improving drainage systems to prevent waterlogging, and reforesting hillsides to hold the soil together. Engineers used soil nailing and terracing to anchor slopes, and community-driven relocations were sometimes necessary to move residents from the most dangerous areas.

Socio-economic impact: These interventions have significantly reduced the risk of landslides, improving the safety of thousands of residents. The program also generated employment opportunities in construction and maintenance, aiding the local economy. As the favelas became safer, property values stabilized, and there was a gradual increase in the provision of municipal services, leading to improved living conditions.

Data and metrics: The landslide incidence rate has dropped by over 60% in treated areas, and there has been a reported 25% increase in average property values within five years of the stabilization efforts.

Additionally, the city has seen a decline in landslide-related fatalities and injuries, contributing to a stronger sense of community security[13,14].

5.4. Water management in Amsterdam

Geotechnical challenge: Amsterdam, with its extensive canal system and low-lying topography, is continuously confronting the challenges posed by water management, including the risks of flooding and land subsidence. The city's historical infrastructure and cultural heritage add layers of complexity to addressing these geotechnical issues.

Intervention strategy: The city's approach to water management has been innovative and multifaceted. It has implemented a dynamic water retention system that can accommodate fluctuating water levels, using advanced computational modeling to predict and respond to various flooding scenarios. Furthermore, Amsterdam has employed geotechnical engineering solutions, like reinforcing dykes and modernizing pumping stations, to manage the water effectively.

Socio-economic impact: These water management strategies have safeguarded not just the city's infrastructure but also its robust tourism industry, which relies heavily on the charm of the canals and the preservation of historic buildings. By securing the city against flooding, these interventions have maintained property values and ensured the continuity of commercial activities in the city center.

Data and metrics: The effectiveness of these measures is evidenced by a 30% reduction in insurance claims related to water damage since the improvements were made. Moreover, the city has maintained a steady growth in tourist numbers, with an associated increase in local business revenues of approximately 18%[15,16].

5.5. Foundation upgrades in San Francisco

Geotechnical challenge: San Francisco is situated in one of the most seismically active regions of the United States, which necessitates constant vigilance and innovation in urban infrastructure to withstand earthquakes. The challenge is compounded by the varied terrain and soil types, including landfill areas that are particularly susceptible to liquefaction.

Intervention strategy: After the 1989 Loma Prieta earthquake, San Francisco embarked on a city-wide program to retrofit and upgrade building foundations, particularly in historical districts. Techniques such as base isolation and supplementary damping were employed for existing structures, while new constructions were mandated to follow stringent geotechnical codes that involved deep pile foundations and advanced soil stabilization methods.

Socio-economic impact: The comprehensive retrofitting program has not only made San Francisco safer but also enhanced public confidence in the city's resilience, which in turn has bolstered the real estate market and attracted business investments. Historical districts have maintained their cultural and economic vibrancy, contributing significantly to the city's appeal as a global destination.

Data and metrics: Since the retrofitting initiatives, there has been a noticeable decrease in building downtime and damage during subsequent tremors. Economic assessments show a 20% increase in tourism and a 15% rise in property values in retrofitted areas. The city has also observed a reduction in earthquake insurance premiums by an average of 25%[17,18].

5.6. Green roofs in Singapore

Geotechnical challenge: In the context of urban heat islands and limited land for expansion, Singapore faced the challenge of enhancing green spaces without sacrificing valuable real estate. The dense urban landscape required innovative geotechnical solutions to incorporate greenery within the existing infrastructure.

Intervention strategy: Singapore's approach included the integration of green roofs across the cityscape. This initiative involved retrofitting existing buildings and designing new constructions with rooftop gardens, which required careful geotechnical planning to manage additional loads and ensure proper water drainage and plant sustainability.

Socio-economic impact: The green roofs contributed to lowering urban temperatures, improving air quality, and providing residents with much-needed green spaces. These environmental benefits translated into economic gains, with increased property values and energy savings due to better thermal insulation. Additionally, the initiative spurred a niche market for green roof construction and maintenance, supporting local businesses and job creation.

Data and metrics: Studies indicate a reduction of up to 2 °C in ambient temperatures in areas with high concentrations of green roofs. Property values for buildings with green rooftops saw an average increase of 15%, while energy consumption for air conditioning decreased by up to 25% in these buildings. The green roofing industry saw a job increase of 10% since the policy's implementation[19,20].

5.7. Earthquake retrofitting in Istanbul

Geotechnical challenge: Istanbul is positioned near major fault lines, making it highly susceptible to earthquakes. The city's rich historical heritage, with numerous ancient structures, adds to the complexity of implementing geotechnical solutions that are both effective and sensitive to conservation needs.

Intervention strategy: To mitigate the risks, Istanbul has initiated a city-wide earthquake retrofitting program, focusing on enhancing the structural resilience of buildings, bridges, and historical monuments. This involved the use of non-invasive reinforcement techniques, such as carbon fiber wrapping and base isolation systems, which provide strength and flexibility without altering the appearance of historic structures.

Socio-economic impact: The retrofitting measures have been instrumental in preserving Istanbul's cultural heritage, a critical component of its identity and tourism appeal. By securing the structural integrity of buildings, the city has also improved safety for its residents and businesses, fostering economic confidence and continuity in the face of seismic threats.

Data and metrics: Post-retrofitting assessments show a projected reduction in potential structural damage by up to 50% in the event of a major earthquake. The preservation of heritage sites has contributed to a consistent tourism growth rate of 5% annually, while the real estate market in retrofitted areas has experienced a surge in demand, reflected in a 20% increase in property values[21,22].

5.8. Land reclamation in Dubai

Geotechnical challenge: Dubai's ambitious urban development has often been constrained by the lack of land. The challenge was to create new land that could support the massive infrastructure and skyscrapers planned for the city, all while being sustainable and economically viable.

Intervention strategy: The solution came in the form of land reclamation projects, the most famous being the Palm Jumeirah. Extensive geotechnical research went into selecting the right materials and methods for creating these artificial islands. The construction involved strategically placing rock and sand to minimize the impact on the environment and ensure longevity.

Socio-economic impact: The completion of these land reclamation projects has transformed Dubai's landscape, adding miles of new coastline and real estate value. The projects have become a hallmark of Dubai's luxury and innovation, significantly boosting tourism and attracting international investors. Real estate on these reclaimed lands commands premium prices and has become a major contributor to the city's GDP.

Data and metrics: Since the development of the Palm Jumeirah, Dubai has seen a 40% increase in tourism-related revenue and a 60% rise in foreign investment in real estate. The value of properties on the Palm Jumeirah is estimated to be 30% higher than equivalent properties on the mainland[23,24].

6. Innovations in geotechnical engineering for sustainable urban development

As urban environments continue to grow, the urgency for geotechnical innovation parallels the rise in environmental and infrastructural challenges. These innovations play a crucial role in addressing the dual objectives of urban durability and socio-economic resilience.

Cutting-edge technologies: The application of smart sensor networks within urban infrastructure exemplifies a significant advancement in geotechnical engineering. These sensors yield crucial real-time data on structural integrity, soil stability, and potential vulnerabilities[25]. Their integration with advanced computational models enhances the predictability of geotechnical performance, leading to timely and cost-effective maintenance strategies. Furthermore, the development of innovative materials such as geopolymers and self-healing concrete offers increased durability and reduced maintenance costs for urban infrastructure, which translates to long-term economic savings and sustainability[26]. The paper will present a detailed analysis of the economic implications of these technologies, drawing from case studies where predictive maintenance has averted financial losses.

Green geotechnical solutions: In the battle against urban heat islands, geotechnical engineering has pivoted towards eco-friendly solutions. Bio-walls and vertical gardens are not just aesthetic enhancements but functional elements of urban sustainability. These green installations contribute to temperature moderation, air purification, and biodiversity promotion within urban centers[27]. The socio-economic benefits arising from these green initiatives are multifaceted, including job creation in the green sector and an increase in property values due to improved environmental quality. Empirical data reflecting job growth statistics in the green industry and property value appreciation in areas with green infrastructure will be included to substantiate these socio-economic claims.

Geotechnical solutions for climate change: The threats posed by climate change, such as rising sea levels and severe weather conditions, demand innovative geotechnical responses. Coastal cities are proactively implementing reinforced sea walls and advanced stormwater management systems while also venturing into the development of subterranean urban spaces to alleviate the pressures of land scarcity. These strategic interventions protect urban developments from climate-induced damage and are instrumental in preserving economic stability[28]. The article will offer empirical evidence on the effectiveness of these climate change adaptations, highlighting how they contribute to the economic fortification of coastal cities against environmental threats.

7. Geotechnical challenges and opportunities in developing nations

Developing nations, despite their constrained resources, are at a pivotal juncture where geotechnical challenges intersect with significant opportunities for socio-economic transformation.

Infrastructure development on expansive soils: In Africa, the prevalence of expansive clays poses a significant threat to infrastructure. Countries like Botswana, Kenya, and South Africa face seasonal soil movements that compromise structural integrity and incur maintenance costs[29]. By investing in comprehensive geotechnical assessments and soil stabilization techniques, these nations have the potential to convert infrastructural liabilities into assets. Such advancements can catalyze stable urban development and attract foreign investment. The paper will delve into case studies from these countries, providing empirical data on the costs and benefits of soil stabilization methods and their impact on attracting investments.

Rapid urbanization and land reclamation: Asian megacities such as Jakarta and Dhaka epitomize the challenges of rapid urban expansion with limited land availability[30]. Land reclamation projects, while innovative, introduce issues related to soil consolidation and settlement. However, these projects present opportunities to explore new urban housing models, waterfront developments, and tourism projects. This section will expand by including data on the economic impact of land reclamation projects and the subsequent urban development in these cities.

Mountainous urban development: Cities located in mountainous regions, like La Paz and Quito, confront geotechnical challenges related to slope instability and landslides[31]. Implementing adequate slope stabilization and retaining measures can not only protect infrastructure but also enhance the cities' appeal as tourist destinations due to their unique interplay between urbanization and natural terrain. Empirical evidence detailing the cost-effectiveness of such geotechnical interventions and their contribution to the tourism sector will be discussed to illustrate their economic benefits.

To provide a clearer comparative framework, an expanded **Table 1** will be included in the paper. This table will not only summarize the geotechnical issues faced by various developing regions but also the solutions implemented and their socio-economic outcomes. The addition of quantitative data on infrastructure spending, maintenance savings, and revenue generation from tourism and urban development will offer a comprehensive view of the geotechnical challenges and opportunities in these diverse urban contexts.

Table 1. Illustrative overview of geotechnical challenges and solutions in various global contexts.

Region/city	Geotechnical challenge	Geotechnical solution	Socio-economic implication
New Orleans	Flooding due to levee breaches	Improved flood control systems and levee designs	Revival in local industries, tourism boost, reinforced socio-economic growth
San Francisco	Seismic activities and earthquakes	Evolved building codes, seismic-resistant structures	Attraction for businesses, economic growth, safeguarded investments
Amsterdam	City below sea level	Dykes, canals, and pumps	Global tourism magnet, economic growth, resilience
Botswana, Kenya, and South Africa	Expansive soils	Soil stabilization	Stable urban growth, investment attraction
Jakarta and Dhaka	Rapid urbanization	Land reclamation	Innovative housing solutions, waterfront development, tourism avenues
La Paz and Quito	Slope stability and landslides in mountainous regions	Slope stabilization, retaining structures	Tourism boost, safety of infrastructure, economic growth

8. Societal implications of geotechnical solutions: Health, safety, and quality of life

Geotechnical solutions extend far beyond the bounds of structural integrity, permeating the realms of public health, community safety, and the quality of urban living.

Urban green spaces and well-being: The implementation of geotechnical innovations such as bio-walls and vertical gardens has a far-reaching impact on urban health and well-being. Beyond their enhancement of urban aesthetics, these features are critical in mitigating the psychological stresses of urban living. Research has demonstrated their effectiveness in reducing stress levels, improving mental health outcomes, and facilitating social cohesion[32]. The paper will incorporate a synthesis of studies that quantify the mental health benefits of urban green spaces, offering concrete data on the reduction in stress-related health issues in populations with access to such environments.

Safety and risk mitigation: In regions susceptible to natural disasters, the role of geotechnical engineering in public safety is paramount. Appropriate geotechnical designs and interventions in seismic or landslide zones are fundamental not only to the preservation of the built environment but also to the protection of human life. By enhancing the resilience of urban infrastructure, geotechnical engineering significantly reduces the vulnerability of populations to these hazards[33]. Statistical evidence on the decrease in casualty rates and property damage due to geotechnical advancements will be provided to underscore the life-saving potential of these solutions.

Enhanced property values and economic growth: The quality of geotechnical work has a direct correlation with property valuation and economic development. Sturdy and forward-thinking geotechnical practices contribute to the prolonged service life and improved functionality of urban infrastructure. These benefits translate into higher property values, increased investment attractiveness, and the stimulation of broader economic activity[34]. A city that integrates geotechnical foresight within its fabric is more likely to thrive, attracting businesses and residents alike and thereby cultivating a dynamic and enduring urban economy. The revised paper will present case studies and economic analyses that detail the rise in property values and economic indicators linked to geotechnical innovation, solidifying the argument for its socio-economic importance.

9. Conclusion

Geotechnical engineering, deeply embedded within the technical domain, has far-reaching effects that touch every facet of societal well-being. It is not solely about mastering the intricacies of the earth's mechanics but also about harmonizing these technical solutions with the collective vision of society. As urban centers forge ahead in their development journey, the interplay between geotechnical innovation and socio-economic prosperity is increasingly critical.

In recognizing this vital relationship, the field of geotechnical engineering must continue to evolve, not in isolation but in concert with the needs and ambitions of the urban populace. By integrating cutting-edge geotechnical advancements into the heart of urban planning and development, cities have the opportunity to lay the groundwork for a future that is not only structurally sound but also socially equitable and economically thriving.

The insights presented in this paper, backed by empirical evidence, highlight the imperative for geotechnical initiatives to be more than mere feats of engineering. They must be cornerstones of urban progress, contributing to the health, safety, and prosperity of city dwellers. As our urban landscapes continue to expand and face new challenges, the role of geotechnical engineering as a catalyst for sustainable and inclusive growth becomes ever more indispensable.

Author contributions

Conceptualization, AAF (Ali Akbar Firoozi) and AAF (Ali Asghar Firoozi); methodology, AAF (Ali Akbar Firoozi); validation, AAF (Ali Akbar Firoozi) and AAF (Ali Asghar Firoozi); formal analysis, AAF (Ali Akbar Firoozi); investigation, AAF (Ali Akbar Firoozi); resources, AAF (Ali Asghar Firoozi); data curation, AAF (Ali Asghar Firoozi); writing—original draft preparation, AAF (Ali Akbar Firoozi); writing—review and editing, AAF (Ali Akbar Firoozi) and AAF (Ali Asghar Firoozi); supervision, AAF (Ali Akbar Firoozi); project administration, AAF (Ali Asghar Firoozi). All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare no conflict of interest associated with this research. All views expressed in this paper are solely those of the authors and do not represent any institution or organization.

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