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RESEARCH ARTICLE

Geotechnical risk management in soft soil construction projects

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Abstract - Geotechnical risk management in soft soil construction projects is critical due to the challenges posed by weak ground conditions. This study presents three case studies that demonstrate different approaches to addressing these challenges. In Case 1, at the Hospital Tengku Ampuan Rahimah Integration Quarters in Klang, improved design measures and enhanced preconstruction practices were applied to reduce settlement risks and ensure structural stability. In Case 2, at the Core Facilities Building of Polytechnic Kota Kinabalu, both immediate and long-term countermeasures were implemented, where short-term monitoring recorded differential settlement of up to 130 mm and long-term predictions ranged between 243–384 mm over 9–14 years. In Case 3, at Batu Kawan, dynamic consolidation combined with prefabricated vertical drains accelerated ground improvement, allowing the treated soil to achieve the required bearing capacity within 126 days. A comparative assessment of the three projects highlights the importance of proactive design, monitoring, and treatment in managing geotechnical risks, providing practical guidance for foundation construction on soft soils.

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1. Introduction

Geotechnical management in soft-soil construction projects is a significant area of study due to the inherent challenges posed by weak and unstable ground conditions. Soft soils are characterised by low shear strength and high compressibility, which can lead to significant issues, including excessive settlement, differential movement, and structural instability if not properly managed. The complexity of these conditions necessitates a comprehensive approach to risk identification, assessment, and mitigation throughout the construction process [1]-[2]. Effective risk management strategies are essential for ensuring project success and safety [3]-[4]. According to research, the management of geotechnical risks involves understanding uncertainties in soil behaviour and implementing appropriate treatment methods to enhance ground stability [5]-[7]. Techniques such as vertical drains, ground improvement methods, and floating foundations are commonly employed to address these challenges. Each method has its own feasibility, cost implications, and efficiency levels, which must be carefully evaluated in the context of specific project requirements [8]. The significance of geotechnical risk management is further emphasised by the potential financial repercussions associated with ground-related challenges. Delays and structural failures may result in considerable cost overruns and project postponements, thereby necessitating a proactive approach to risk management by stakeholders [9]-[10]. By integrating advanced monitoring techniques and construction control measures, project teams can more effectively anticipate issues and implement prompt interventions. In conclusion, geotechnical risk management in soft-soil construction projects extends beyond addressing present challenges; it also involves planning for future uncertainties[11]. A systematic approach that includes comprehensive site investigations, continuous monitoring, and adaptive management is essential for achieving successful outcomes in these complex environments [12]-[15].

2. Case Studies

2.1 Case Study 1: Hospital Tengku Ampuan Rahimah Integration Quarters in Klang, Selangor

2.1.1 Project background

The project involved constructing three blocks of 13- and 14-story integration quarters at the existing hospital compound, initiated in 2007 under a design-and-build concept. The site was underlain by very soft to soft silty clay, 15-20 meters thick, followed by medium-stiff to stiff silty clay and sandy clay, with a hard stratum at depths of 18-28 meters [16]-[17]. Concrete spun piles with a diameter of 500 mm with a design capacity of 850 kN were used for the foundation system [18]. Furthermore, to minimise noise and vibration near the existing structures, the jacked-in method was adopted for installing the piles. However, no ground treatment was performed to enhance the soft soil's engineering properties.

2.1.2 Risk Identification

Numerous critical risks were identified during the construction phase. The soft soil presented a considerable geotechnical challenge due to its low shear strength and high compressibility, rendering it susceptible to excessive vertical and lateral displacements under load [16]-[18]. Piling issues were evident as illustrated in Figure 1, shows that the installed piles exhibited deviations and tilting resulting from soil displacement caused by the jacked-in machine. Furthermore, the failure to verify pile positions prior to installation exacerbated the issues. Excavation operations for the lift pits uncovered additional hazards. The temporary sheet pile walls were inadequately designed, reaching only 6 m instead of the mandated

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9 meters. Substandard construction practices, including placing excavated earth atop the pit crest, increased the surcharge loading. In summary, design deficiencies and construction errors significantly contributed to these challenges.

Figure 1. Sheet piles and piles adjacent to the excavation pit tilted

2.1.3 Risk assessment

Risks associated with this project were assessed to be severe, given their impact on structural integrity and project timelines. The likelihood of these issues occurring was medium to high due to the site's soft soil conditions and improper planning. Collectively, the challenges led to significant delays, additional costs for replacing damaged piles, and the need for corrective measures to address the structural and geotechnical failures [19].

2.1.4 Mitigation strategies

To address the identified risks, several mitigation strategies were proposed. First, improved design and preconstruction preparations were necessary, including ground treatment methods such as soil stabilisation or preloading to enhance soil stability [18]. Adequate depth and strength of temporary sheet-pile walls were critical for effectively retaining excavation areas. Enhanced construction practices were also recommended. Proper working platforms should be established before pile installation, and excavated material should be placed away from the pit to reduce surcharge loads. Rigorous monitoring and quality control measures were essential to ensure that pile positions were regularly checked and that geotechnical investigations validated the design under real-world conditions [16]. Additionally, contractor training and enhanced supervision were emphasised. Clear guidelines on construction in soft soil conditions and strict adherence to best practices and design specifications were vital. By implementing these strategies, future projects could effectively mitigate or avoid similar challenges.

2.2 Case Study 2: Core Facilities Building of Polytechnic Kota Kinabalu, Sabah

2.2.1 Risk identification

The Core Facilities Building of Polytechnic Kota Kinabalu (PKK) as shown in Figure 2 faced significant geotechnical challenges due to construction on soft ground [20]. The risks were identified through extensive investigations and assessments. Differential settlement was observed, with columns settling at varying rates, causing structural cracks in the Core Facilities Building and the Teaching Restaurant. Ground settlement within the building compound was recorded at 130 mm (103 mm/year), indicating active settlement at the time of investigation. Soil investigations revealed a 7.2 m thick fill layer acting as a surcharge load on a 10.6–11.6 m thick, soft, compressible clayey sandy silt layer, resulting in significant consolidation settlement [21]. Additionally, the pile-driving records highlighted improper installation criteria, as negative friction was not considered in the pile design. Thus, it reduces the net allowable bearing capacity and causes the pile to be overloaded.

Figure 2. Block A and B Polytechnic Kota Kinabalu, Sabah

2.2.2 Risk Assessment

Risk assessments were conducted using a range of techniques, including settlement analysis, monitoring activities, and structural proof-checking. Predictions for magnitude and rate of anticipated settlement due to the 7.2 m thick of fill material as in Table 1 indicated post-settlement of 243 mm and 384 mm for boreholes 1A and 2A, respectively, with a consolidation period of 9–13.7 years [21]-[22]. Column settlement monitoring revealed a maximum settlement of 52 mm within 15 months, confirming ongoing differential settlement. The analysis of pile capacity presented in Table 2 showed that the negative skin friction reduced the effective capacity from 629 kN to 412 kN, contributing to the foundation's instability. These findings underscore the necessity of a comprehensive understanding of subsoil profiles and their consolidation behaviour when constructing on soft ground [23].

Table 1. Magnitude and rate of anticipated settlement due to the 7.2 m thick of fill material

BH Location	Thickness of Compressible Layer (m)	Time Required for 90% Consolidation (year)	Predicted Post Settlement after 5 years (mm)
1A	10.6	9.06	243
2A	11.6	13.7	384

Table 2. Pile allowable bearing capacity

Allowable Pile Bearing Capacity (kN)	Negative Skin Friction (kN)	Nett Allowable Bearing Capacity (kN)
629	217	412

2.2.3 Risk mitigation strategies

Mitigation strategies included immediate and long-term measures. Immediate actions such as condition surveys, crack mapping, and structural proof-checking helped assess the extent of the damage. Long-term solutions recommended included redesigning pile foundations to account for negative skin friction, conducting load tests on shorter piles, and employing ground improvement techniques such as preloading or vertical drains to accelerate settlement [20], [24]. Repairs to the drainage system were also proposed to address settlement-related issues. Continuous monitoring of settlement and structural performance was emphasized to ensure timely intervention. Additionally, material and design reviews were recommended to align structural designs with geotechnical realities, ensuring the stability and longevity of the building. These measures demonstrate the importance of integrating geotechnical investigations, risk assessments, and mitigation strategies in managing construction risks on soft soils effectively [25]-[26].

2.3 Case Study 3: Batu Kawan Project

2.3.1 Risk identification

The Batu Kawan project encountered the following risks due to the discovery of an existing layer of soft marine clay at the site [27]-[28]. The project as illustrated in Figure 3 was to build a gallery and show house for a housing development that was required to be constructed on a fast-track basis. The primary concern was the undesirable amount of settlement the clayey bearing subsoil presented to the structure [21]. Natural consolidation at the site took longer due to the soil’s low permeability, delaying the construction schedule. It was also evident that untreated soil had inadequate bearing capacity, and its value was unable to achieve the target of 200 kPa required for the project. Furthermore, the application of conventional surcharge preloading, which required 2.0 m of fill material, was problematic due to its high cost and logistical impracticalities, given the high demand for fill material. Such risks required a robust improvement strategy to enable construction to proceed safely and quickly [29].

(a) Completed sales gallery

(b) Show houses nearing completion

Figure 3. Sales gallery and nearing-completion houses

2.3.2 Risk assessment

To assess the site conditions, comprehensive subsoil investigations were performed. The subsoil profile primarily consisted of normally consolidated clay, with borehole Standard Penetration Test *N* values ranging from 0 to 30 meters [27]. These values were generally below 10, indicating that the soil should be classified as weak and compressible [30]. The coefficient of consolidation (C_v) varied from 1 to 4 m²/year, reflecting a slow drainage rate of excess pore water pressure. Additionally, the recompression index (C_c) was approximately 0.2, providing further evidence of the soil's high compressibility. An over-consolidation ratio close to 1 further confirmed the soil's weakness. Other geotechnical instruments, including rod settlement gauges, piezometers, and inclinometers, were utilised to monitor settlement, pore water pressures, and lateral displacements throughout the construction process. Piezometer readings indicated that dynamic consolidation induced excess pore water pressures of up to 30 kPa, at a surcharge level equivalent to 1.5 meters, thereby validating this method for achieving the desired soil improvement [31].

2.3.3 Risk mitigation strategies

To mitigate the identified risks, the following measures have been implemented. Engineers employ a technique known as dynamic consolidation. In the treatment of soft ground, surcharge fill is utilised to increase soil stress, thereby elevating pore-water pressure, known as excess pore-water pressure. Since soft clays exhibit low permeability, the drainage of this excess pressure occurs gradually. To expedite this process, vertical drains are installed, reducing the drainage pathway and enhancing the efficiency of pressure dissipation [32]-[33]. This consolidation process can be modelled through a simplified system comprising a spring and a water-filled container with a minor aperture in the lid, as depicted in Figure 4. The spring symbolises the soil's compressibility, while the water represents the pore water within the soil.

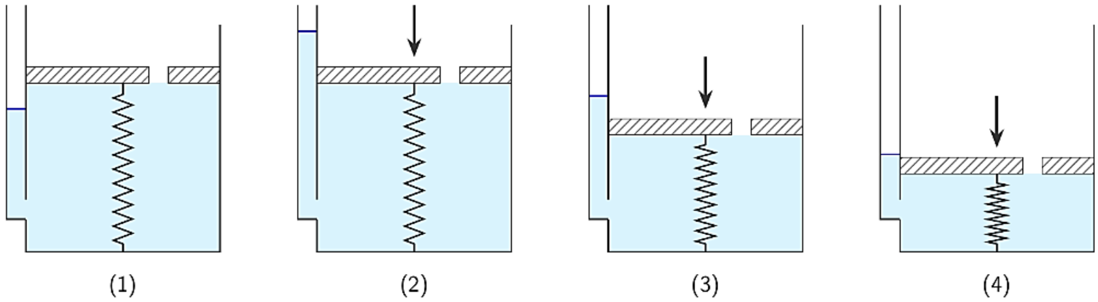

Figure 4. Idealised concept of 1-dimensional consolidation process

i) The container is entirely filled with water, and the hole remains sealed. (Soil is fully saturated)
ii) A load is applied to the top while the hole stays closed. At this point, the water alone bears the applied load. (Excess pore water pressure builds up)
iii) Once the hole is opened, water begins to escape, and the spring compresses. (Excess pore water pressure begins to dissipate)
iv) After a while, the water stops draining. At this stage, the spring solely supports the load. (Excess pore water pressure is fully dissipated, and consolidation is complete.

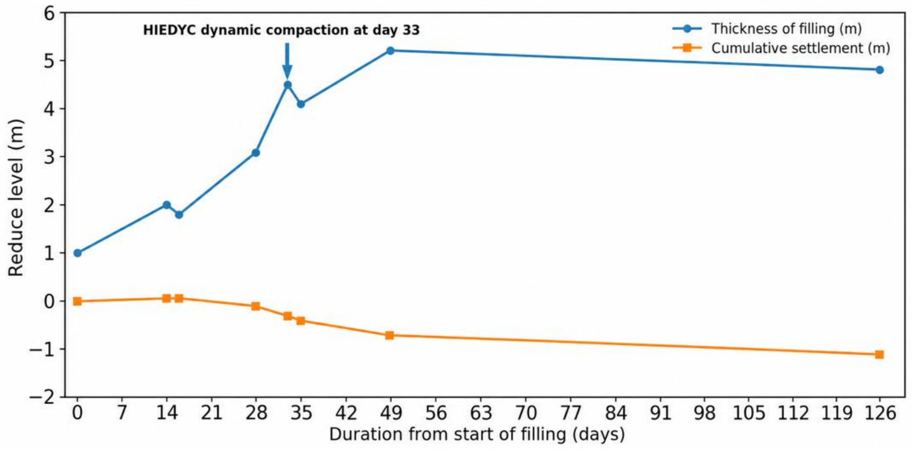

Figure 5. Typical ground settlement profile at the sales gallery

In this project, engineers employ two methodologies for consolidation: High Impact Energy Dynamic Compaction (HIEDYC) [31] and Prefabricated Vertical Drains (PVD) [32]. The ground improvement techniques utilised are advanced and serve to enhance building designs. HIEDYC was implemented at the sub-base layer fill and the design platform, facilitating greater consolidation by rapidly generating pore water, thereby reducing the need for extensive surcharge fills [31], [34]-[35]. PVDs were installed at 1.0 m spacing to expedite the dissipation of pore water pressures and thus enhance the rate of soil consolidation [31]. Consequently, the surcharge fill height was reduced from 2.0 metres to 1.0 metres to optimise material usage and decrease project costs. Additionally, the newer type of geosynthetic strip drains, which consists of an aged, horizontally drained sand layer, ensures a continuous water flow regardless of the sand supplied [24]. The compaction of fill material was conducted using vibratory rollers in accordance with the project earthwork plan to ensure uniformity. Monitoring of settlements showed that consolidation was achieved within 126 days, with settlements measuring 1.2 meters at the sales gallery and 1.05 meters at the show houses, as anticipated. Plate Bearing Tests confirmed that the soil's bearing capacity was enhanced, with recorded settlements of less than 3 mm at 200 kPa and less than 8 mm at 400 kPa, thereby meeting the project specifications. Figure 5 and Figure 6 illustrate the soil settlement profile of the project areas.

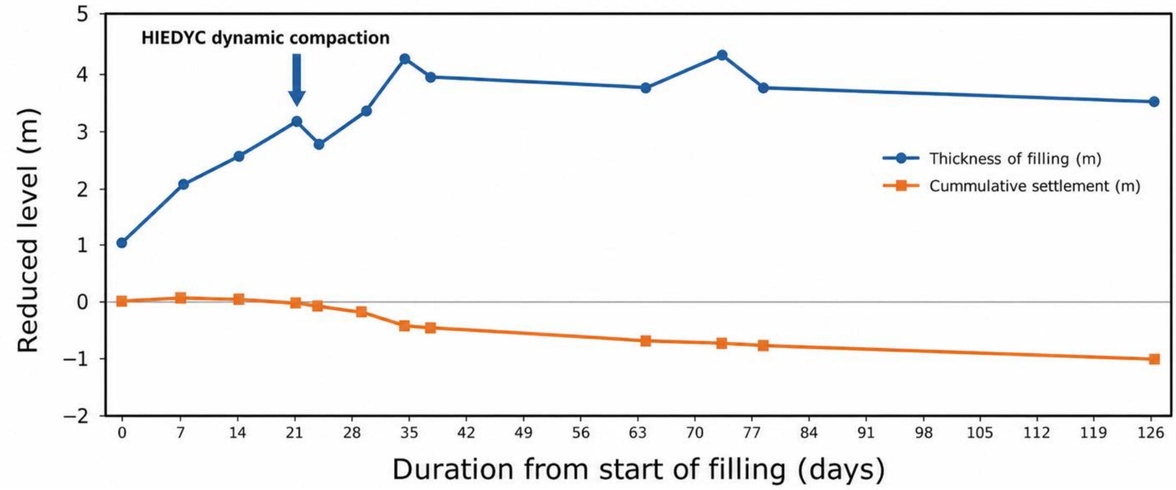

Figure 6. Typical settlement profile at show houses

3. Comparative Analysis

Table 3 and Table 4 presenting summaries of the comparison and risk assessment matrix of the three case studies that have been focused on [36]-[40]. The comparison provides a comprehensive evaluation of the different ground improvement approaches adopted to address soft soil challenges, together with the associated risks, likelihood, consequences, and corresponding mitigation measures [41]-[44]. In Case 1 (Jacked-In Piles), to mitigate noise and vibration near existing hospital structures, a jacked-in pile system was employed [18]. However, the ground displacement caused tilting and deviation of the piles due to insufficient treatment of the soft ground, which exhibited minimal resilience and high compressibility. Furthermore, Case 2 incorporated preloading and drainage techniques. Stress preloading with the existing fill layer imposed a surcharge load, leading to consolidation settlement [21]. Negative skin friction on the piles diminished their load-bearing capacity and underscored the need for effective pile design and management to prevent uneven settlement. Lastly, High Impact Energy Dynamic Compaction (HIEDYC) was utilised to dynamically consolidate the soil [31], generating immediate pore-water pressures which were subsequently drained via Prefabricated Vertical Drains to enhance soil consolidation [32]. Compared to previous methods, this approach reduced the surcharge fill from 2.0 meters to 1.0 m, thereby minimising material usage and costs, while ensuring uniform settlement.

The foundation improvement approaches differed significantly among the three cases. Case 1 used piles without improving the soil. This left the foundation prone to moving sideways and up and down when weight was applied to it. Case 2 placed extra weight on top to squeeze water out of the soil over time, but it was slow because there was no way for the water to drain. Case 3 used the HIEDYC method to shake the soil, trapping water pressure equal to 1.5 meters of extra soil on top. They also put in special drains to let the water out. This made the soil get stronger much faster [31], [32]. The methods' success varied across cases. Case 1 saw pile problems and significant building delays because they didn't improve the ground and instead designed temporary sheet-pile walls, which made digging riskier. Case 2 had long-term settlement issues, with post-settlement values ranging from 243mm to 384mm over 9–13.7 years [21]. This meant they had to fix and redesign elements to address differential settlement and weaker piles. On the other hand, Case 3 settled in 126 days. It hit its settling goals of 1.2m for the sales gallery and 1.05m for the show houses. Plate Bearing Tests showed it could bear 200 kPa, with tiny settlings of under 3 mm at 200 kPa and under 8mm at 400 kPa. This proved the method worked much better. The significance and appropriateness of the methods for soft soil conditions varied substantially. In Case 1, solely employing piles without addressing soil instability proved ineffective for soft soils. The jacked-in technique mitigated vibrations but did not resolve the fundamental issue of instability. Case 2 demonstrated the critical importance of preloading and consistent monitoring to manage settlement risks. However, neglecting the use of vertical drains and implementing suboptimal pile design diminished effectiveness and prolonged the stabilisation process. Case 3 proved to be the most successful for soft soils, integrating HIEDYC with prefabricated vertical drains (PVDs) to deliver a comprehensive solution. This combination of dynamic compaction and improved drainage accelerated consolidation and reduced material costs. It addressed both squishiness and drainage issues directly. Among the three cases, Case 3 (Batu Kawan) proved the most effective and efficient solution to soft-soil challenges. The integration of HIEDYC and PVDs delivered significant improvements in soil strength and settlement control, as well as faster consolidation and cost savings. This highlights the importance of advanced ground improvement techniques and careful design considerations in managing construction risks on soft soils.

Table 3. A comparative table summarising the three case studies

Case	Case 1: Hospital Tengku Ampuan Rahimah	Case 2: Polytechnic Kota Kinabalu	Case 3: Batu Kawan
Project Description	3 blocks of 13- and 14-story integration quarters	Core Facilities Building and Teaching Restaurant	Construction project on soft marine clay
Subsoil Characteristics	Soft silty clay (15-20 m), medium stiff silty clay below	7.2 m fill layer over 10.6–11.6 m compressible clayey silt	Normally consolidated marine clay with low permeability
Foundation System	Concrete spun piles (500 mm diameter, 850 kN capacity)	Pile foundation (negative skin friction overlooked)	Dynamic compaction with reduced surcharge fill and PVDs
Key Risks	• Low shear strength and high compressibility of soft clay • Pile tilting due to soil displacement • Improper excavation and surcharge loading on pits	• Differential settlement causing structural cracks • Negative skin friction reduced pile capacity	• Low bearing capacity and excessive settlement • Slow drainage of excess pore water pressure
Risk Assessment	• Severe risks with medium to high likelihood • Delays and extra costs for replacing damaged piles	• High post-settlement predicted (243–384 mm) • Differential column settlement (up to 52 mm in 15 months)	• Monitoring showed high compressibility and weak soil • Slow natural consolidation due to low permeability
Outcomes	• Improved pile installation practices and fewer delays • Lessons learned for future soft soil construction	• Structural stability maintained through monitoring • Comprehensive geotechnical investigations recommended	• Faster consolidation achieved with reduced material costs • Bearing capacity improved, meeting project specifications
Settlement Rates	Settlement leveled off in 126 days (1.2 m and 1.05 m)	Maximum column settlement of 52 mm in 15 months	Settlement completed in 126 days with improved bearing capacity

Table 4. Risk assessment matrix of the three case studies

Case	Key Risks	Likelihood	Consequence	Risk Level	Mitigation Strategies
Case 1: Hospital Tengku Ampuan Rahimah	Low shear strength, pile tilting, surcharge loading	Medium - High	Severe (delays, damaged piles)	High	Ground treatment, deeper sheet piles, improved monitoring
Case 2: Polytechnic Kota Kinabalu	Differential settlement, negative skin friction	High	Severe (structural cracks, reduced capacity)	High	Redesign piles, preload, vertical drains, monitoring
Case 3: Batu Kawan	Differential settlement, negative skin friction	Medium	Moderate–Severe (delays, weak soil)	Medium - High	Dynamic compaction prefabricated vertical drains, reduced surcharge

4. Conclusions

The analysis of these three cases underscores the importance of selecting appropriate methods for soft-ground improvement in foundation construction. This case illustrates that neglecting proper soil enhancement and relying solely on piling without ground improvement exacerbates issues and causes construction delays. Furthermore, as demonstrated in Case 2, settlement risks necessitate preloading; however, existing methods have yielded unsatisfactory results before installing drainage systems and designing piles, leading to consolidation and persistent problems. Based on the three cases, Case 3 emerges as the most effective, as the implementation of HIEDYC and PVDs provided a comprehensive approach that achieved rapid consolidation, enhanced soil strength, and cost reduction. Our assessment indicates that Case 3 underscores the need to develop innovative techniques to accurately predict the compressibility and drainage characteristics of soft soils. Consequently, this method fulfils both performance and stability criteria and is therefore recommended for use in similar future projects.

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Declaration of Competing Interest
The author declares no conflicts of interest.

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U. F. Mohd Giman (Methodology; Analysis; Writing – original draft)
M. D. H. Matdaim (Conceptualisation; Writing – original draft)
D. Z. Abang Hasbollah (Writing -revise & review ; Supervision)
B. A. Othman (Conceptualisation; Supervision; Writing-revise & review)
A. M. Taib (Analysis; Resources; Writing – original draft)
R. M. Bhatawdekar (Conceptualisation; Writing – original draft)

Availability of Data and Materials
The data supporting this study’s findings are available on request from the corresponding author.

Ethics Declarations
This study did not involve human participants or animals. Ethical approval was therefore not required.

Generative Artificial Intelligence Declarations
The authors claim that artificially intelligent-assisted technologies, such as generative AI, were not used to generate content, ideas, or theories. We have just utilised AI to enhance readability and refine the language. This was used with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

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