Molecular & Cellular Biomechanics 2025, 22(4), 783.
https://doi.org/10.62617/mcb783

Article

Mechanical characteristics and construction strategy optimization for foundation design in complex geological conditions

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CITATION

Han N. Mechanical characteristics and construction strategy optimization for foundation design in complex geological conditions. Molecular & Cellular Biomechanics. 2025; 22(4): 783. https://doi.org/10.62617/mcb783

ARTICLE INFO

Received: 13 November 2024
Accepted: 18 November 2024
Available online: 28 February 2025

Abstract: In order to improve the reliability and efficiency of foundation design in complex geological environments, this paper proposes a computer-assisted mechanical characterization model based on biomechanical principles, which is combined with bionic design methods to optimize the construction strategy. By integrating the stress distribution and deformation mechanism of biomaterials, this paper designs a foundation structure that is more adaptable to the geological uncertainty, and uses optimization algorithms and dynamic feedback mechanisms to analyze the foundation bearing capacity, settlement control and structural response. The results show that the optimized model significantly improves the foundation safety, reduces the overall construction cost, and provides valuable guidance for engineering practice.

Keywords: biomechanics; complex geological conditions; foundation design; mechanical characterization; soil-structure interaction

1. Introduction

In the field of geotechnical engineering, the design of foundations in complex geologic environments has always been a challenging task [1,2]. The stability and safety of foundations are essential for the integrity and long-term performance of any structure. However, achieving these goals is often hampered by the numerous factors that characterize such environments. Complex geologic environments are typically composed of heterogeneous soil layers. These layers can vary in composition, density, and mechanical properties [3,4]. For example, some regions may have soft clayey soils that are highly compressible [5,6], while others may contain sandy or gravelly soils with different load-bearing capacities. The variation in soil properties can lead to differential settlement, where different parts of the foundation experience unequal vertical displacements. This can cause structural damage and compromise the overall stability of the building or infrastructure. Groundwater is another critical factor that affects foundation design. The presence of water in the soil can increase pore water pressure, reducing the effective stress and shear strength of the soil. In some cases, this can lead to soil liquefaction, a phenomenon that can have disastrous consequences during seismic events. Additionally, groundwater flow can cause erosion and scour around the foundation, undermining its support and stability.

Structural loads, which are transmitted to the foundation from the superstructure, also play a significant role. These loads can be static, such as the dead weight of the building, or dynamic, including wind, seismic, and live loads. The accurate determination and distribution of these loads are essential for designing a foundation that can safely support the structure [7]. However, predicting the actual loads and their effects on the foundation is often difficult due to the uncertainties associated with the structure’s use and the environment. Conventional design methods have been developed to address these challenges, but they often rely on simplified assumptions and empirical correlations [8]. These methods may not fully capture the complexity and variability of real-world geologic conditions. As a result, there is a need for more advanced and innovative design approaches.

Biomechanical principles, especially biomimetic design methods, offer a promising solution. Nature has evolved a wide range of materials and structures with remarkable properties. Biomaterials, such as spider silk and shell structures, are known for their high stability and adaptability. Spider silk, for instance, has an outstanding strength-to-weight ratio and can withstand significant tensile forces [9]. Shell structures exhibit excellent compressive strength and resistance to fracture [10]. By studying and emulating these natural materials and structures, engineers can gain new insights into the design of infrastructure. The hierarchical organization and unique material properties of biomaterials can inspire the development of novel foundation designs. For example, the self-assembly and self-healing mechanisms observed in some biomaterials could be applied to create more resilient foundation systems.

In this study, we aim to explore the application of biomaterials’ properties to the design of foundations in complex geologic conditions. We will establish biomechanical models to understand the behavior of these materials under various loading and environmental conditions. These models will be based on experimental data and advanced computational techniques. To optimize the foundation design, we will combine the biomechanical models with optimization algorithms. These algorithms will search for the best design parameters, such as the geometry and material distribution of the foundation, to maximize its load-bearing capacity and minimize settlement. Furthermore, we will incorporate a dynamic feedback mechanism into the design process. This will involve the use of sensors to monitor the performance of the foundation during construction and operation. The data collected from these sensors will be used to update the biomechanical models and optimization algorithms, allowing for real-time adjustments and improvements to the design. In conclusion, this research represents an innovative approach to foundation design in complex geologic environments. By incorporating biomechanical principles and advanced technologies, we hope to develop more efficient and reliable foundation systems. The findings of this study could have significant implications for the construction industry, leading to safer and more sustainable infrastructure.

2. Mechanical characteristics in complex geological conditions

2.1. Classification of geological conditions

Geological conditions are classified based on soil and rock types, structural integrity, groundwater level, and other factors. Common types include soft soil, sandy soil, cohesive soil, and bedrock. Soft and sandy soils have low bearing capacity and are prone to settlement, while cohesive soils have variable bearing capacity due to moisture fluctuations [11]. Integrating biomechanics principles can enhance the understanding of soil-structure interaction. For example, studying natural materials like honeycomb structures offers design insights for improving foundation stability and resistance to deformation, particularly in weak soils. These structures efficiently distribute loads, reducing settlement and improving stability. Engineering parameters, such as shear strength and internal friction angle of cohesive soils, are determined through triaxial compression and shear tests. This classification and the associated design conditions (**Table 1**) provide a reliable basis for foundation design, while offering a biomimetic approach to strengthening foundation structures.

Table 1. Mechanical characteristic parameters of typical geological conditions.

Geological Type	Shear Strength (kPa)	Internal Friction Angle (°)	Bearing Capacity Factor	Saturated Density (kg/m^3)
Soft Soil	10–30	15–20	0.5–0.8	1700–1800
Sand Soil	20–40	30–35	1.0–1.5	1800–1900
Clay Soil	15–50	20–25	0.8–1.2	1900–2100
Rock Layer	Above 100	Above 45	Above 3.0	Above 2500

2.2. Analysis of foundation bearing capacity

Under complex geological conditions, foundation bearing capacity calculation is mainly based on factors such as geological type, soil layer distribution and soil mechanical parameters, and usually adopts calculation methods such as ultimate bearing capacity method and foundation settlement control method [12]. Foundation bearing capacity formulas can be selected according to different geological conditions, and the typical formulas are Bergen formula and Meyerhof formula:

$$q_u = c \times N_c + \sigma \times N_q + 0.5 \times \gamma \times B \times N_\gamma \tag{1}$$

where, q_u is the ultimate bearing capacity, c is the soil cohesion, σ is the surface overload, γ is the soil gravity, B is the foundation width, N_c, N_q, N_γ,is the bearing capacity coefficient, which is related to the internal friction angle of the soil body [13]. To verify the model’s applicability, a typical engineering project was selected, substituting bearing capacity data of various geological layers into the model. Its validity under different conditions was tested by comparing actual observations with model calculations.

The project, located in an area complex geology (soft, sandy, clayey soils, and rock layers), used mechanical characteristics (e.g., cohesion, internal friction angle, gravity) to calculate bearing capacity values (**Table 2**). The soft soil layer, with low bearing capacity, required reinforcement, while the sandy and clayey layers met design requirements. On-site test results closely matched model predictions, confirming the model’s accuracy in reflecting actual geological conditions.

Biomechanical principles have introduced new ideas for foundation design. For example, biomimetic design can replicate the structural properties of shells, which are known for their high strength and efficient stress distribution. Imitating their geometry and stress patterns can enhance the stability and deformation resistance of foundations in weak soils. This approach allows for more uniform bearing capacity distribution, reducing foundation settlement and improving overall safety [14].

Table 2. Foundation bearing capacity parameters for typical geological conditions.

Geological Type	Cohesion c (kPa)	Density γ (kN/m^3)	Internal Friction Angle (°)	N_c	N_q	N_γ
Soft Soil	10–15	17–19	15–20	12–20	5–10	2.5–5.5
Sand Soil	0	18–20	30–35	0	25–30	15–20
Clay Soil	15–30	18–21	20–25	15–25	10–15	5–8
Rock Layer	Above 100	Above 25	Above 25	Above 30	Above 40	Above 30

2.3. Foundation settlement characteristics

Foundation settlement characteristics show significant layer differences and time-dependent properties under complex geological conditions, and settlement prediction is usually carried out through the layered sum method and elastic half-space theory [15]. Foundation settlement (S) can be calculated from the compression modulus and layer thickness with the equation:

$$S = \sum \frac{\Delta\sigma \times H}{E_S} \tag{2}$$

where $\Delta\sigma$ is the additional stress, H is the thickness of the soil layer, and E_S is the compression modulus of the soil layer. Foundation settlement can be calculated by considering the compression modulus, thickness, and additional stress of each soil layer, and calibrated with measured data for accuracy. **Table 3** outlines typical settlement characteristics under complex geological conditions, including soft ground creep, sandy soil transient settlement, and clayey soil long-term settlement, providing essential design data [16]. Controlling settlement is crucial for maintaining structural safety and stability, with settlement analysis during construction ensuring deformation control.

Biomechanical principles offer new solutions for settlement control. Biomimetic design, such as mimicking honeycomb structures, optimizes settlement by distributing stress evenly and reducing local settlement impacts [17]. Applying this concept to foundations in complex geological conditions, particularly in soft and clayey soils, can enhance settlement control, improve foundation stability, and reduce uneven settlement.

Table 3. Foundation settlement parameters for typical geological conditions.

Geological Type	Compression Modulus E_S (Mpa)	Additional Stress $\Delta\sigma$ (kPa)	Layer Thickness H (m)	Typical Settlement S (mm)
Soft Soil	1–5	50–100	5–10	50–200
Sand Soil	10–30	100–150	3–5	10–30
Clay Soil	5–10	80–120	5–8	30–100
Rock Layer	Above50	Above150	Below 3	Below 5

To verify the model's accuracy, we used the "A commercial and residential complex in Xiamen," located in a complex geological area with soft, sandy, and clayey soils. The model predicted the settlement for each layer: 200 mm for soft soil, 30 mm for sandy soil, and 90 mm for clayey soil. During construction, the actual settlements were 180 mm, 25 mm, and 85 mm, respectively. These results confirm the model's high accuracy in predicting foundation settlement under complex geological conditions.

3. Computer-aided optimization model of foundation design and construction strategy

3.1. Construction of mechanical characteristics analysis model

The construction of mechanical characteristic analysis model is aimed at providing high-precision mechanical prediction and analysis tools for foundation design through computer-aided means and comprehensive consideration of foundation stress, deformation and settlement characteristics under complex geological conditions. The model construction is based on elastic mechanics and finite element analysis methods, firstly, the mechanical parameters of each soil layer are discretized and the foundation structure model is established by grid division [18]. The stress-strain relationship equation is:

$$\sigma = E \times \varepsilon \tag{3}$$

where, σ is stress, E is elastic modulus, and ε is strain. The model uses numerical iteration to find the optimal solution through stress and strain calculations, calibrated with field test data. For limited data or geological surveys, simplified models based on empirical formulas can provide preliminary guidance by setting parameter ranges for typical geological types and estimating bearing capacity or settlement through interpolation (see **Table 4**).

This study also introduces biomechanics to optimize the simulation of soil layer mechanical properties through biomimetic design [19]. For example, mimicking stress distribution in natural materials like shells and spider silk can improve compressive capacity and deformation control. In areas with significant settlement, such as soft soil and clay, biomechanical optimization enhances settlement control and improves model design accuracy.

Table 4. Parameter input requirements for mechanical characterization model.

Parameter	**Soft Soil**	**Sand Soil**	**Clay Soil**	**Rock Layer**
Elastic Modulus E (Mpa)	1–5	10–30	5–10	Above 50
Compression Modulus E_S (Mpa)	1–5	10–30	5–10	Above 50
Layer Thickness H (m)	5–10	3–5	5–8	Below 3
Strain ε	0.01–0.05	0.005–0.02	0.01–0.03	Below 0.001

3.2. Design of construction optimization algorithm

The construction optimization algorithm aims to improve foundation strategy by dynamically adjusting parameters under complex geological conditions to ensure stability and cost control. Using biomechanical principles and intelligent optimization methods (e.g., Genetic Algorithm GA and Simulated Annealing SA), the algorithm iteratively searches for optimal parameter combinations through selection, crossover, and mutation operations [20]. The goal is to minimize total settlement and construction cost while meeting foundation bearing capacity, safety, and settlement control constraints. The optimization objective function can be expressed as:

$$min\big(f(x) = \alpha \times C(x) + \beta \times S(x)\big) \tag{4}$$

where $f(x)$ is the optimization objective value, $C(x)$ is the construction cost function, $S(x)$ is the settlement function, and α, β is the weight coefficient, reflecting the importance of cost and settlement control. In data-constrained field environments, rule-based or heuristic optimization methods quickly determine construction parameters. For instance, foundation reinforcement is prioritized at points with low bearing capacity, and settlement-cost balance is evaluated using empirical weights for rapid optimization.

By adjusting input parameters and weights, the algorithm assesses the model's applicability under different geological conditions and converges to an optimal solution through iterations, enabling intelligent control of construction parameters for safety and cost efficiency. **Table 5** lists input parameters and weight settings, where each adjustment impacts results.

Construction cost and settlement weights (0.3–0.7) reflect their equal importance. Proper weight settings balance safety and cost, minimizing expenses while meeting safety standards. The number of iterations (10–1000) improves accuracy, while the SA range (1000–5000) influences exploration depth. The GA crossover rate (0.6–0.8) boosts search diversity, and the mutation rate (0.01–0.05) prevents premature convergence while maintaining exploration.

Table 5. Input parameters and weight settings of construction optimization algorithm.

Parameter	**Value Range**
Construction Cost Weight α	0.3–0.7
Settlement Weight β	0.3–0.7
Iteration Count	100–1000
SA	1000–5000
GA (Crossover Rate)	0.6–0.8
GA (Mutation Rate)	0.01–0.05

3.3. Dynamic feedback and adjustment mechanism

The dynamic feedback mechanism optimizes the construction strategy in real time by monitoring foundation settlement, stress distribution, and deformation, feeding this data into the computer-aided model [21]. It involves four steps: sensor acquisition, data transmission, feedback analysis, and parameter adjustment. To improve data acquisition, portable sensors and multi-source data fusion are used. Portable displacement meters collect settlement data, while UAV remote sensing captures stress distribution, reducing collection time. Edge computing preprocesses data in real time, with key parameters input directly into the model to enhance feedback speed and applicability.

Sensors at key locations monitor foundation response, and data is wirelessly transmitted for analysis. If deviations are detected, the system generates an adjustment plan, which is fed back to the site for optimization. **Figure 1** illustrates the workflow of the dynamic feedback mechanism, supporting construction in complex geological conditions.

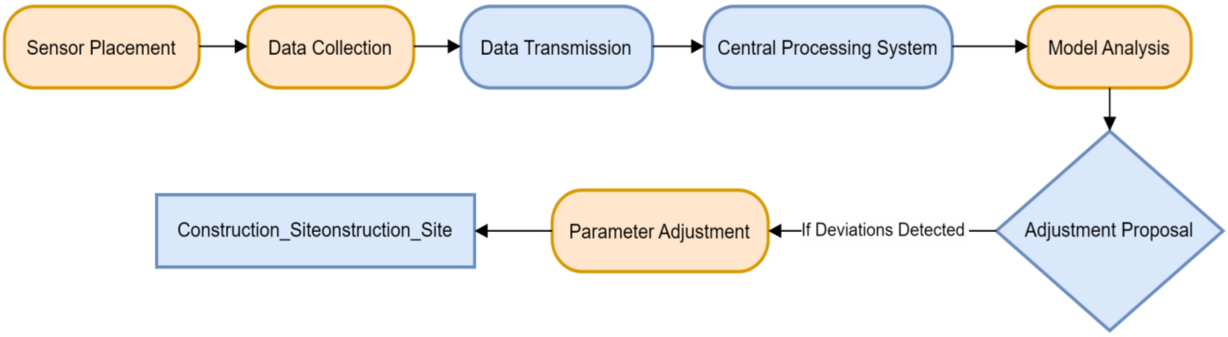

Figure 1. Schematic diagram of dynamic feedback and adjustment mechanism.

4. Result and discussion

4.1. Mechanical characterization results of foundation design

The mechanical characterization results show that under complex geological conditions, the stress distribution and deformation of soil layers significantly impact the foundation's bearing capacity and settlement control. By analyzing parameters such as elastic modulus, compression modulus, and internal friction angle, settlement and stress distribution under various loads are calculated [22]. For example, model validation for soft soil, clayey soil, and sandy soil in the "underground station of a section of Hangzhou subway" shows that the soft soil layer exhibits larger settlement, with stress concentrated in the middle of the basement and a lower safety coefficient, requiring reinforcement. The clayey soil layer shows smaller settlement, less stress concentration, and a higher safety coefficient, while the sandy soil layer demonstrates excellent stability and bearing capacity. Field monitoring data shows settlements of 115 mm, 42 mm, and 18 mm for soft soil, clayey soil, and sandy soil, respectively, closely matching the model's predictions, confirming its reliability across different geological conditions (**Figure 2**).

Additionally, biomechanical optimization is introduced. By simulating the stress distribution of natural materials (e.g., shell and honeycomb structures), foundation design can be further optimized to improve bearing capacity and stability, reducing the risk of uneven settlement [23]. In conditions with large settlement, such as soft and clayey soils, biomechanical optimization effectively enhances design outcomes and improves construction safety and reliability.

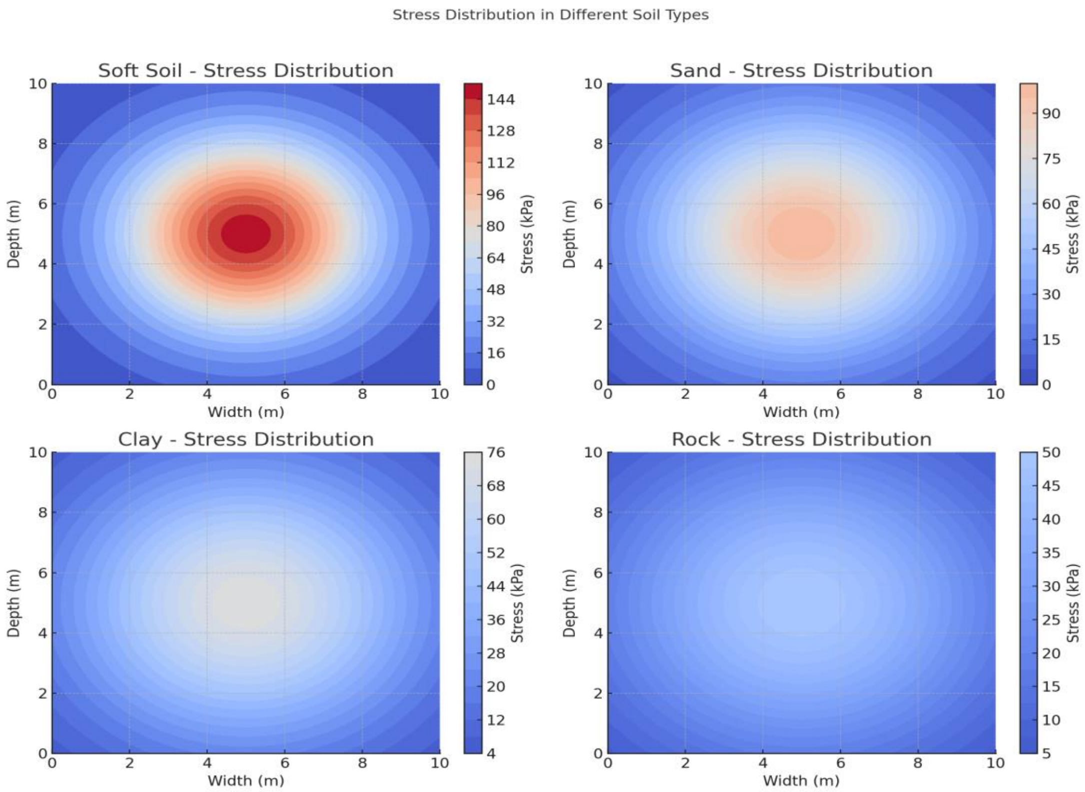

Figure 2. Stress distribution cloud diagram under typical geological conditions.

Table 6 shows significant differences in foundation mechanical characteristics across geological types, highlighting varying impacts on bearing capacity and stability. The soft soil layer has the largest settlement (50–200 mm) and a stress concentration area of 5–10 meters, indicating low bearing capacity and high deformation potential, which can lead to excessive settlement and safety concerns. In contrast, the sandy soil layer has smaller settlement (10–30 mm) and a smaller stress concentration area (3–5 m), demonstrating better bearing capacity and easier settlement control. The clay layer experiences settlement of 30–100 mm and a stress concentration area of 4–8 m, with a safety coefficient of 1.6–2.0, indicating good stability but some settlement risk. Foundation design on clay layers must account for these properties to ensure safety. The rock layer shows minimal settlement (less than 5 mm), a small stress concentration area (under 2 m), and a safety coefficient greater than 3.0, indicating superior bearing capacity and stability, making rock formations ideal for large buildings or heavy structures.

To further improve foundation stability and safety, this study suggests incorporating biomechanical principles [24]. By simulating the stress distribution of structures such as shells and honeycombs, biomimetic design can enhance the mechanical properties of soil layers and optimize settlement control. This approach is especially effective in soft and clayey soils, improving foundation stability and bearing capacity.

Table 6. Mechanical characterization results under different geological conditions.

Geological Type	Calculated Settlement (mm)	Stress Concentration Area (m)	Safety Factor
Soft Soil	50–200	5–10	1.2–1.5
Sand Soil	10–30	3–5	1.8–2.2
Clay Soil	30–100	4–8	1.6–2.0
Rock Layer	Less than 5	Less than 2	Above 3.0

4.2. Construction strategy optimization effect

The optimization analysis shows that the model based on genetic and simulated annealing algorithms significantly improves foundation bearing capacity and settlement control. The optimized scheme effectively reduces settlement, construction costs, and improves foundation stability. After several iterations, the objective function converges to the optimal parameter combination. **Table 7** compares data before and after optimization, showing reductions in settlement, stress concentration, and construction costs. After optimization, the settlement of the soft soil layer is reduced by over 30%, stress concentration in sandy and clayey soils is alleviated, and the bearing capacity utilization of the rock layer increases by 20%.

The biomechanical optimization design further enhances the foundation's bearing capacity and stability while optimizing material utilization. By simulating natural stress distributions (e.g., shell and honeycomb structures), material consumption is reduced without compromising strength, optimizing foundation design and improving construction efficiency and stability.

Table 7. Comparison of effect before and after construction strategy optimization.

Geological Type	Settlement Before Optimization (mm)	Settlement After Optimization (mm)	Construction Cost Before Optimization (10,000 CNY)	Construction Cost After Optimization (10,000 CNY)	Bearing Capacity Utilization Improvement (%)
Soft Soil	150	100	50	40	15
Sand Soil	30	20	45	38	12
Clay Soil	80	50	55	47	10
Rock Layer	5	4	70	63	20

Figure 3 shows the convergence curve of the objective function in the process of construction optimization, which demonstrates the effect of iterative optimization under various geological conditions, verifies the practicability and applicability of the optimization algorithm under complex geological conditions, and provides strong data support for the actual construction.

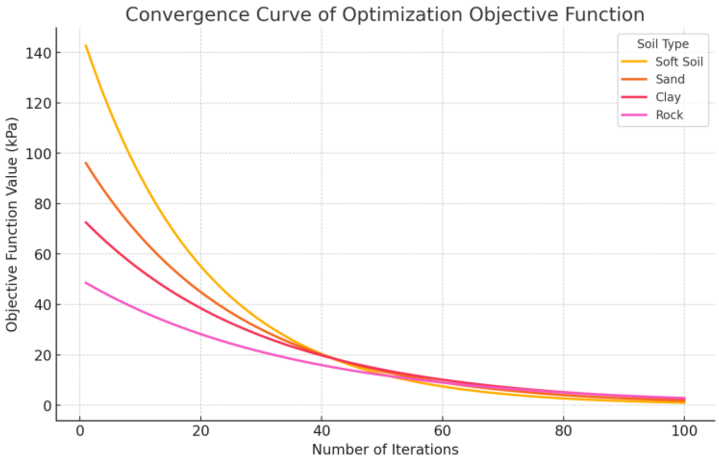

Figure 3. Convergence curve of objective function of construction strategy optimization.

4.3. Model limitations and suggestions for improvement

Although the computer-assisted foundation design optimization model improves construction outcomes in complex geological conditions, it has limitations in data accuracy, algorithm complexity, and applicability. The model depends on finite element analysis and simulation data, so errors in input parameters affect accuracy [15]. Engineering data shows the model struggles to predict long-term creep in soft soils, particularly secondary settlement during later construction stages. Additionally, relying on accurate input data can lead to error accumulation when field data is scarce, and the computational demands of finite element analysis and optimization algorithms may reduce efficiency in large-scale projects. To improve practicality, a simplified model based on empirical formulas or regression analysis could offer rapid predictions in preliminary design. Using portable sensors and UAV remote sensing for multi-source data collection, combined with real-time calibration via edge computing, can optimize the dynamic feedback mechanism, enhancing prediction accuracy and adaptability.

To further improve model accuracy and efficiency, biomechanical optimization could be introduced. By simulating the stress distribution of natural structures, model calculations can be simplified, improving prediction accuracy. This would enhance design stability, reduce computation time, and lower costs in large-scale projects.

5. Discussion

In the domain of foundation design within complex geological settings, the integration of advanced techniques and the application of principles from related fields such as biophysics can significantly enhance the overall process [25]. The stability and safety of foundations are of paramount importance, as they form the basis for any structure, and their design must be optimized to withstand the challenges presented by the geological environment. Accurate data regarding the mechanical characteristics and bearing capacity of the soil is the cornerstone of a successful foundation design. This parallels the need for precise measurements in biophysical studies. For example, in analyzing the biomechanics of biological materials like tendon or ligament, the determination of their elastic modulus, tensile strength, and viscoelastic properties with high precision is essential to understand their performance under different loading conditions [26,27]. Similarly, in foundation design, the shear strength, Young’s modulus, and Poisson’s ratio of the soil must be accurately quantified. Any inaccuracies in these data can lead to overestimation or underestimation of the foundation’s capacity, potentially resulting in structural failures or excessive deformations [28]. Computer-assisted design and feedback mechanisms have transformed the foundation design process. In biophysics, computational models are extensively used to simulate the behavior of biological structures. For instance, finite element analysis has been applied to model the stress and strain distribution in bones, helping researchers understand how they respond to physiological loads and how fractures occur [29].

In foundation design, computer simulations can predict the settlement and stress patterns of the soil, allowing engineers to optimize the foundation’s geometry and reinforcement layout. The feedback loop, analogous to the homeostatic mechanisms in biological systems that maintain stability, enables real-time adjustments during construction. If the measured parameters such as settlement or stress deviate from the predicted values, the design can be modified promptly, improving construction efficiency and the overall quality of the foundation. The combination of optimization algorithms and dynamic feedback is a powerful tool. In the context of biophysical design, genetic algorithms and other optimization techniques have been used to design biomimetic structures. For example, in the development of artificial joints, optimization algorithms are employed to find the optimal material combination and surface topography to mimic the natural joint’s kinematics and load-bearing characteristics. In foundation design, these algorithms can search through a vast design space, considering variables such as the thickness and spacing of reinforcement bars, the depth and width of the foundation, and the type of soil improvement techniques. By integrating dynamic feedback, the design can be continuously refined to achieve the best performance. Looking ahead, the introduction of multi-source data fusion and parallel computing technologies holds great potential.

In biophysical research, data from multiple sources such as genomics, proteomics, and imaging are integrated to gain a comprehensive understanding of biological systems. In foundation design, geological survey data, geophysical measurements, and historical construction records can be combined to create a more accurate model. Parallel computing can accelerate the analysis of complex data and simulations. In biomechanics, it enables the simulation of large-scale biological systems or the analysis of complex loading scenarios. In foundation design, it can handle the vast amount of data generated by sensors and simulations, especially in extreme conditions such as earthquakes or high groundwater levels. The application of convolutional neural networks (CNN) and long short-term memory (LSTM) networks in foundation design is promising. In biophysics, CNNs have been used for image analysis, such as identifying cellular structures or detecting diseases from medical images. In foundation design, CNNs can analyze geological images and maps to identify potential geological hazards or soil heterogeneity. LSTMs, which are effective in handling time-series data, can predict the long-term behavior of the foundation, such as the evolution of settlement over time. In biophysical systems, LSTMs can predict the growth and development of organisms or the progression of diseases. In foundation design, they can provide valuable insights for long-term maintenance and the assessment of the foundation's performance. In conclusion, by adopting the principles and techniques from biophysics and other advanced fields, the optimization of foundation design in complex geological conditions can be greatly enhanced. The strict control of data accuracy, the utilization of computer-assisted and feedback mechanisms, and the exploration of emerging technologies will lead to more reliable, efficient, and sustainable foundation designs, ensuring the safety and stability of structures in challenging geological environments. This interdisciplinary approach will open up new avenues for innovation and improvement in the field of foundation engineering.

6. Conclusion

Optimizing foundation design under complex geological conditions requires strict control of data accuracy in mechanical characteristics and bearing capacity analysis, along with computer-assisted and feedback mechanisms to improve construction efficiency. By integrating optimization algorithms and dynamic feedback, precise control of foundation construction is achieved. In the future, multi-source data fusion and parallel computing technologies can be introduced to enhance the model's breadth and accuracy under extreme conditions. For example, using convolutional neural networks (CNN) or long short-term memory (LSTM) networks for pattern recognition of historical geologic data and prediction of stress and settlement distributions can further improve the model's accuracy and utility in data-scarce scenarios.

Ethical approval: Not applicable.

Conflict of interest: The author declares no conflict of interest.

References

1. Jindal S, Rahmanli U, Aleem M, et al. Geotechnical challenges in monopile foundations and performance assessment of current design methodologies. Ocean Engineering. 2024; 310: 118469. doi: 10.1016/j.oceaneng.2024.118469
2. Zhang Q, Zhang H, Wang L, et al. Effect of structural characteristics on the stability of multi-weak rock slopes considering the spatial variability of geotechnical parameters. Scientific Reports. 2024; 14(1). doi: 10.1038/s41598-024-82296-9
3. Studziński R, Ścigałło J, Ratajczak M, et al. Impact of Heterogeneous Soil Conditions on the Life Cycle Assessment of a Multi-Storey Reinforced Concrete Structure. Sustainability. 2024; 16(16): 6771. doi: 10.3390/su16166771
4. Jin Z, Jin YF, Yin ZY, et al. Evolution of bearing capacity and macroelement modelling for suction caisson foundations in sand considering local scour. Computers and Geotechnics. 2025; 179: 106985. doi: 10.1016/j.compgeo.2024.106985
5. Hosseinpour I, Almeida MSS, Riccio M, et al. Strength and Compressibility Characteristics of a Soft Clay Subjected to Ground Treatment. Geotechnical and Geological Engineering. 2017; 35(3): 1051-1066. doi: 10.1007/s10706-017-0161-8
6. Salimi M, Ghorbani A. Mechanical and compressibility characteristics of a soft clay stabilized by slag-based mixtures and geopolymers. Applied Clay Science. 2020; 184: 105390. doi: 10.1016/j.clay.2019.105390
7. Puri VK, Prakash S. Foundations for Dynamic Loads. In Art of Foundation Engineering Practice. 2010; 517-533. doi: 10.1061/41093(372)26
8. Otake Y, Honjo Y. Challenges in geotechnical design revealed by reliability assessment: Review and future perspectives. Soils and Foundations. 2022; 62(3): 101129. doi: 10.1016/j.sandf.2022.101129

9. Gosline JM, Guerette PA, Ortlepp CS, et al. The mechanical design of spider silks: from fibroin sequence to mechanical function. Journal of Experimental Biology. 1999; 202(23): 3295-3303. doi: 10.1242/jeb.202.23.3295
10. Meyers MA, Chen PY, Lin AYM, et al. Biological materials: Structure and mechanical properties. Progress in Materials Science. 2008; 53(1): 1-206. doi: 10.1016/j.pmatsci.2007.05.002
11. Guo L, Du D, Li W, et al. Efficiency of in-wall weave patterns on the mechanical properties of integrally woven carbon/carbon honeycomb structures. Journal of Sandwich Structures & Materials. 2024; 27(3): 651-671. doi: 10.1177/10996362241308557
12. Onyelowe KC, Mojtahedi FF, Ebid AM, et al. Selected AI optimization techniques and applications in geotechnical engineering. Cogent Engineering. 2022; 10(1). doi: 10.1080/23311916.2022.2153419
13. Martinez A, Dejong J, Akin I, et al. Bio-inspired geotechnical engineering: principles, current work, opportunities and challenges. Géotechnique. 2022; 72(8): 687-705. doi: 10.1680/jgeot.20.p.170
14. Zhao Y, Dai S. Challenges of rock drilling and opportunities from bio-boring. Biogeotechnics. 2023; 1(1): 100009. doi: 10.1016/j.bgtech.2023.100009
15. Rahimi B, Sharifzadeh M, Feng XT. A comprehensive underground excavation design (CUED) methodology for geotechnical engineering design of deep underground mining and tunneling. International Journal of Rock Mechanics and Mining Sciences. 2021; 143: 104684. doi: 10.1016/j.ijrmms.2021.104684
16. Rayfield EJ. Finite Element Analysis and Understanding the Biomechanics and Evolution of Living and Fossil Organisms. Annual Review of Earth and Planetary Sciences. 2007; 35(1): 541-576. doi: 10.1146/annurev.earth.35.031306.140104
17. Zhang W, Xiang J, Huang R, et al. A review of bio-inspired geotechnics-perspectives from geomaterials, geo-components, and drilling & excavation strategies. Biogeotechnics. 2023; 1(3): 100025. doi: 10.1016/j.bgtech.2023.100025
18. Li Z, Lv J, Xie X, et al. Mechanical Characteristics of Structures and Ground Deformation Caused by Shield Tunneling Under-Passing Highways in Complex Geological Conditions Based on the MJS Method. Applied Sciences. 2021; 11(19): 9323. doi: 10.3390/app11199323
19. Wang Q, Gao H, Jiang B, et al. In-situ test and bolt-grouting design evaluation method of underground engineering based on digital drilling. International Journal of Rock Mechanics and Mining Sciences. 2021; 138: 104575. doi: 10.1016/j.ijrmms.2020.104575
20. Ma X, Liu Z, Wang W, et al. Characteristics of physical parameters and predictive modeling of mechanical properties in loess-like silty clay for engineering geology. Engineering Geology. 2024; 339: 107672. doi: 10.1016/j.enggeo.2024.107672
21. Zhang Y, Wang X, Jiang C, et al. Biomechanical research of medial femoral circumflex vascularized bone-grafting in the treatment of early-to-mid osteonecrosis of the femoral head: a finite element analysis. Journal of Orthopaedic Surgery and Research. 2022; 17(1). doi: 10.1186/s13018-022-03335-7
22. Zhang D. Seismic Performance Assessment and Enhancement Strategies for Civil Engineering Structures. Academic Journal of Science and Technology. 2024; 10(1): 155-158. doi: 10.54097/40bet123
23. Kashani AR, Chiong R, Mirjalili S, et al. Particle Swarm Optimization Variants for Solving Geotechnical Problems: Review and Comparative Analysis. Archives of Computational Methods in Engineering. 2020; 28(3): 1871-1927. doi: 10.1007/s11831-020-09442-0
24. Platt GM, Yang XS, Silva Neto AJ, et al. Computational Intelligence, Optimization and Inverse Problems with Applications in Engineering. Springer International Publishing; 2019. doi: 10.1007/978-3-319-96433-1
25. Dong X. Effective Approaches of Interdisciplinary Collaboration In the Foundation Design Course. Interdisciplinary Practice in Industrial Design. Published online 2024. doi: 10.54941/ahfe1005124
26. Formenton ABK, de Mello Roesler CR, Vassoler JM. Biomechanical properties of tendons and the relationship with their microstructure. Journal of the Brazilian Society of Mechanical Sciences and Engineering. 2024; 46(8). doi: 10.1007/s40430-024-05068-6
27. Galbusera F, Innocenti B. Ligament and tendon biomechanics. Human Orthopaedic Biomechanics. Published online 2022: 137-149. doi: 10.1016/b978-0-12-824481-4.00016-0
28. Pieczyńska-Kozłowska J, Vessia G. Spatially variable soils affecting geotechnical strip foundation design. Journal of Rock Mechanics and Geotechnical Engineering. 2022; 14(3): 886-895. doi: 10.1016/j.jrmge.2021.10.010
29. Pant A, Paul E, Niebur GL, et al. Integration of mechanics and biology in computer simulation of bone remodeling. Progress in Biophysics and Molecular Biology. 2021; 164: 33-45. doi: 10.1016/j.pbiomolbio.2021.05.001