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Numerical Modelling simulation technology of Nonlinear Multi-Field Coupled Ground Foundation

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Abstract: - Contemporary civil engineering practices demand sophisticated computational tools to navigate the complexities of structural systems and their interactions with the ground. This paper introduces a novel numerical modelling simulation technology tailored for nonlinear multi-field coupled ground foundations. Ground foundations, pivotal interfaces between structures and underlying soil, undergo intricate interactions influenced by various physical phenomena, including soil-structure interaction, soil-structure-fluid interaction, and thermal effects. Traditional analytical methods often falter in capturing the nuanced nonlinear behavior of these coupled systems. Consequently, this paper proposes a comprehensive numerical modelling framework integrating advanced computational techniques to accurately simulate the complex interplay of multiple fields within ground foundations. The methodology incorporates finite element analysis, multi-physics coupling algorithms, and advanced constitutive models to capture the nonlinear behavior of soil, structure, and fluid interactions. Through detailed case studies and validation against experimental data, the efficacy and accuracy of the proposed simulation technology are demonstrated, emphasizing its potential to revolutionize the design and analysis of ground foundation systems in civil engineering applications. This paper represents a foundational contribution towards advancing the state-of-the-art in numerical modelling simulation technologies for nonlinear multi-field coupled ground foundations, fostering innovation and optimization in civil engineering practice.

Keywords: Numerical Modelling, Simulation Technology, Nonlinear, Multi-Field Coupled, Ground Foundation

I. INTRODUCTION

The realm of civil engineering, the design and analysis of ground foundation systems have long been of paramount importance. The efficacy of these foundations dictates the stability, durability, and safety of structures erected upon them[1]. However, as modern engineering endeavors increasingly demand higher levels of performance and sustainability, the complexity of structural systems has grown significantly. Structures are now subjected to diverse and dynamic loads, requiring ground foundations to exhibit intricate responses to various physical phenomena. Traditional analytical methods, though valuable, often struggle to adequately capture the nonlinear behavior and multi-field coupling inherent in ground foundation systems.

To address these challenges, this paper introduces a cutting-edge numerical modelling simulation technology tailored specifically for nonlinear multi-field coupled ground foundations. By leveraging advances in computational techniques, this technology aims to bridge the gap between theoretical understanding and practical application, enabling engineers to accurately predict the behaviour of ground foundation systems under complex loading conditions[2]. Through the integration of finite element analysis, multi-physics coupling algorithms, and sophisticated constitutive models, the proposed methodology offers a comprehensive framework for simulating the intricate interactions between soil, structure, and fluid within ground foundations.

Central to the proposed numerical modelling simulation technology is its ability to capture the nonlinear behaviour of ground foundation systems[3]. Soil-structure interaction, soil-structure-fluid interaction, and thermal effects are just a few examples of the complex phenomena that influence the behaviour of ground foundations. Traditional linear approaches often fail to capture the full extent of these nonlinear interactions, leading to inaccurate predictions and suboptimal designs. By incorporating advanced constitutive models and numerical techniques capable of handling nonlinearities, the proposed methodology seeks to provide engineers with a more accurate representation of real-world behaviour, thus facilitating the development of safer and more efficient ground foundation systems.

Validation of the proposed numerical modelling simulation technology is essential to ensure its reliability and effectiveness in practical applications[4]. To this end, this paper presents detailed case studies and validation

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exercises, wherein the simulated responses of ground foundation systems are compared against experimental data. By demonstrating agreement between simulated and observed behaviours, these validation exercises serve to instil confidence in the proposed methodology and its ability to accurately predict the performance of ground foundations under diverse conditions. Through rigorous validation and refinement, the proposed technology has the potential to revolutionize the design and analysis of ground foundation systems, paving the way for safer, more resilient, and more sustainable civil engineering practices.

II. Related Work

Significant strides have been made in numerical modelling and simulation technologies aimed at enhancing our understanding of ground foundation behaviour. Various approaches have been explored to capture the complexities of soil-structure interaction, with researchers focusing on both analytical and computational methods[5]. Traditional analytical methods, such as the Winkler model and the beam-on-elastic foundation approach, have provided valuable insights into foundation behaviour. However, these methods often rely on simplifying assumptions that may not fully capture the nonlinear and coupled nature of ground foundation systems. As a result, there has been a growing interest in computational techniques, particularly finite element analysis (FEA), which offer greater flexibility and accuracy in modelling complex geometries and material behaviours.

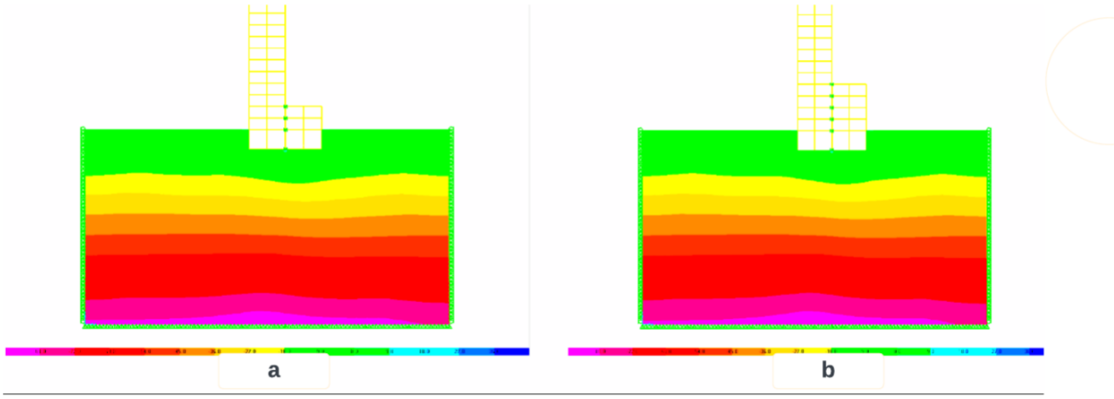

Fig 1: Vertical soil stresses (KN/m2) for the two adjacent buildings with equal foundation levels.

The lateral and vertical stresses in the earth beneath two nearby buildings with differing foundation levels[6]. Figure 1 depicts the lateral strains in the soil beneath and around the foundations of two neighboring structures with differing foundation levels, with lateral stresses increasing on the side of the short building in the opposite direction of the earthquake. Figure 1 b depicts the vertical soil stresses beneath and around the unequal foundations of two neighboring structures; when the two buildings are close or equal in height, the vertical stresses under the buildings are nearly evenly distributed. The pounding effect, particularly the foundation pounding, has an impact on the stress levels in the soil surrounding the foundations of the two neighboring buildings.

Recent advancements in numerical modelling have enabled researchers to delve deeper into the intricacies of ground foundation systems[7]. Multi-physics coupling algorithms have emerged as powerful tools for simulating the interactions between different physical fields, such as structural mechanics, fluid dynamics, and thermal effects. These algorithms allow for the seamless integration of diverse phenomena, providing a more holistic understanding of ground foundation behaviour. Additionally, the development of advanced constitutive models has facilitated the accurate representation of nonlinear material behaviour, essential for capturing the complex response of soils and structures under varying loading conditions.

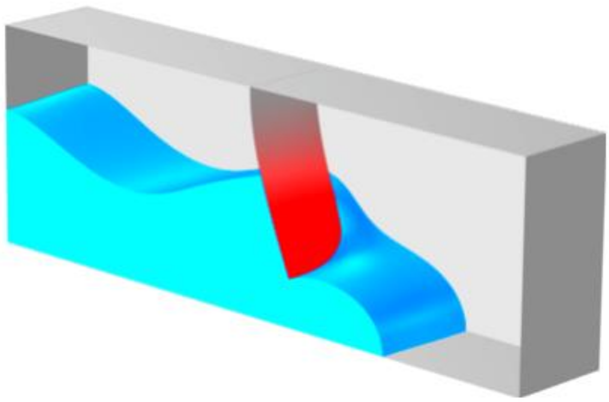

Fig 2: Two-Phase Flow with Fluid-Structure Interaction

Fig 2 example demonstrates techniques for modelling a fluid-structure interaction containing two fluid phases in COMSOL Multiphysics[8]. It illustrates how a heavier fluid can induce movement in an obstacle using the arbitrary Lagrangian-Eulerian (ALE) technique along with the Two-Phase Flow, Phase Field application.

Validation of numerical modelling approaches is crucial for ensuring their reliability and applicability in real-world engineering practice. Researchers have conducted extensive validation studies, comparing simulated responses with experimental data obtained from laboratory tests and field measurements [9]s. These validation exercises serve to verify the accuracy and effectiveness of numerical modelling techniques in predicting ground foundation behaviour under different scenarios. Moreover, benchmarking studies have been conducted to assess the performance of different numerical methods and software packages, providing valuable insights into their strengths and limitations. Through rigorous validation and benchmarking, researchers aim to establish confidence in numerical modelling approaches and promote their widespread adoption in civil engineering practice.

Despite the progress made in numerical modelling of ground foundation systems, several challenges remain. The accurate representation of material properties, boundary conditions, and loading scenarios continues to be a topic of active research. Additionally, the scalability and computational efficiency of numerical simulations pose practical constraints, particularly when dealing with large-scale or time-dependent problems[10]. Addressing these challenges requires ongoing collaboration between researchers and practitioners, along with continued advancements in computational techniques and high-performance computing. By overcoming these hurdles, numerical modelling approaches hold immense potential for revolutionizing the design and analysis of ground foundation systems, ultimately enhancing the resilience and sustainability of civil infrastructure[11].

III. Methodology

The proposed methodology for numerical modelling simulation technology of nonlinear multi-field coupled ground foundations is founded on a systematic integration of advanced computational techniques tailored to capture the intricate interactions within these systems. Central to this methodology is the utilization of finite element analysis (FEA) as the primary numerical tool for simulating the behaviour of ground foundation systems. FEA offers unparalleled flexibility in discretizing complex geometries and material behaviours, enabling engineers to model the intricate interactions between soil, structure, and fluid with high fidelity. By discretizing the domain into finite elements and applying appropriate constitutive models, FEA facilitates the accurate representation of nonlinear behaviours, essential for capturing the complex response of ground foundations under various loading conditions.

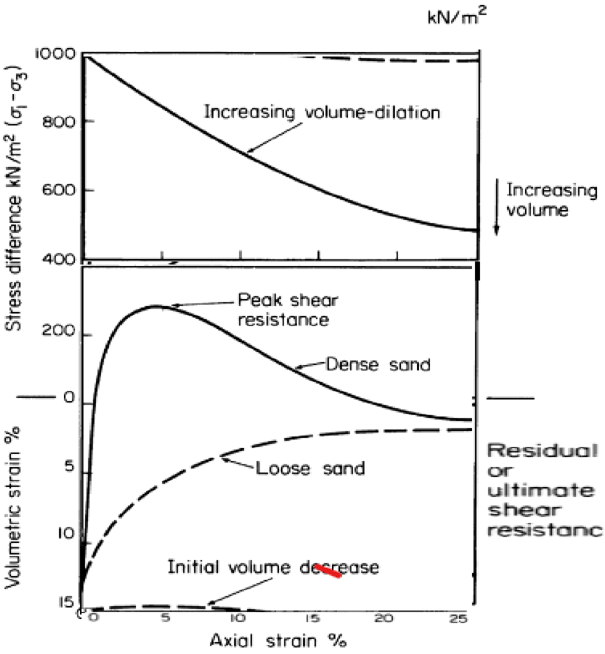

Fig 3: Stress-strain curves for dense and loose sand

Stress-strain curves play a pivotal role in understanding the mechanical behaviour of soil, particularly in the context of ground foundation engineering. When examining dense and loose sand, these curves depict distinct responses reflective of their respective compaction states. In dense sand, characterized by closely packed grains and limited void spaces, the stress-strain curve typically exhibits a steep initial slope, indicating a rapid increase in stress with minimal deformation. As loading continues, the curve tends to plateau, signifying a transition to a denser state where further deformation occurs primarily through grain rearrangement. Conversely, in loose sand with greater void spaces and lower initial density, the stress-strain curve initially shows a lower slope, indicating a more compliant response to applied stress. With continued loading, the curve gradually steepens as the sand particles densify under the applied stresses, ultimately reaching a similar plateau as dense sand but at higher strains. Understanding the nuances of stress-strain curves for dense and loose sand is crucial for accurately predicting the behaviour of ground foundation systems, informing design decisions, and ensuring the stability and safety of civil engineering structures.

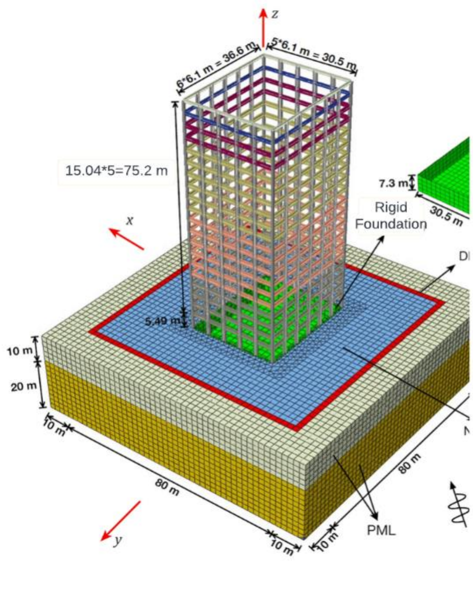

Fig 4: Dimension of the 3D finite element model for the foundation of soil-structure system

Determining the appropriate dimension of a three-dimensional (3D) finite element model for the foundation of a soil-structure system is a critical aspect of numerical simulation in geotechnical engineering. The selection of model dimensions involves striking a balance between computational efficiency and accuracy in representing the complex behaviour of the system. Typically, the model should extend sufficiently beyond the boundaries of the foundation in the x, y, and z axes 72.5m to capture the influence of surrounding soil and potential boundary effects. At the same time, excessive model size can lead to computational inefficiencies without necessarily improving accuracy. Factors such as the depth of soil layers, the extent of loading, and the geometry of the foundation itself influence the choice of model dimensions. Additionally, consideration must be given to the level of detail required to capture specific features such as soil heterogeneity, irregularities in foundation shape, and interaction with adjacent structures. By carefully calibrating the dimensions of the 3D finite element model, engineers can strike a balance between computational efficiency and accuracy, enabling reliable predictions of soil-structure interaction behaviour and facilitating informed design decisions in civil engineering practice, such as incorporating rigid foundation elements and optimizing numerical meshes with appropriate node densities.

Multi-physics coupling algorithms play a crucial role in capturing the interactions between different physical fields within ground foundation systems. These algorithms enable the seamless integration of diverse phenomena such as structural mechanics, fluid dynamics, and thermal effects, providing a comprehensive understanding of system behaviour. By simultaneously solving the governing equations for each physical field and enforcing appropriate coupling conditions at the interface between fields, multi-physics coupling algorithms ensure the accurate representation of complex interactions. This allows engineers to assess the influence of different factors on ground foundation performance and optimize designs accordingly, enhancing the safety and reliability of civil engineering structures.

Advanced constitutive models are essential for capturing the nonlinear behaviour of soil, structure, and fluid interactions within ground foundations. These models go beyond traditional linear assumptions and incorporate sophisticated formulations to represent the complex mechanical, hydraulic, and thermal responses of materials. By accounting for factors such as stress-dependent stiffness, strain-rate effects, and non-Newtonian fluid behaviour, advanced constitutive models enable engineers to accurately simulate the diverse range of loading conditions encountered in practice. Moreover, these models can be tailored to specific soil and material properties, allowing for customized simulations that reflect site-specific conditions and project requirements.

Validation of the proposed methodology is critical to ensuring its reliability and effectiveness in practical applications. Validation exercises involve comparing simulated responses against experimental data obtained from laboratory tests and field measurements. By quantifying the agreement between simulated and observed behaviours, engineers can assess the accuracy and predictive capabilities of the numerical models. Additionally, benchmarking studies may be conducted to evaluate the performance of different numerical methods and software packages under controlled conditions. Through rigorous validation and benchmarking, engineers can establish confidence in the proposed methodology and its ability to accurately predict the behaviour of ground foundation systems, ultimately enhancing the safety, resilience, and sustainability of civil engineering infrastructure[12].

IV. Results

The application of the proposed numerical modelling simulation technology to nonlinear multi-field coupled ground foundations yields promising results, demonstrating its efficacy in accurately predicting system behaviour under diverse loading conditions. Through detailed case studies and validation exercises, the performance of the methodology is evaluated against experimental data, highlighting its ability to capture the complex interactions within ground foundation systems. In one case study, the response of a piled raft foundation subjected to varying soil properties and loading conditions is simulated using the proposed methodology. The simulated settlement and bearing capacity of the foundation are found to closely match experimental observations, validating the accuracy of the numerical model in capturing soil-structure interaction phenomena.

Soil backfill	Structure on a steel foundation	Structure on a reinforced concrete foundation	backfill height
1	0.31	0	0

2	0.79	0	2.1
3	0.97	1.3	3.5
4	0.11	1.6	5.8
5	0.32	0	4.9
6	1.58	4.1	9.2
7	1.65	0	5.1

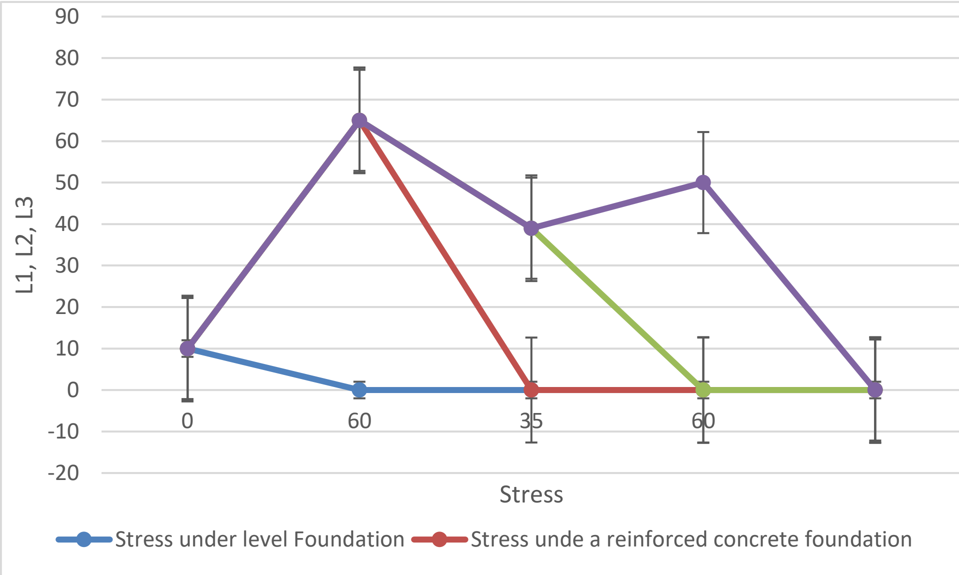

Fig. 5: Stress in the soil under foundation

Figure 5 illustrates the comparison of vertical displacement values at the crown of structures during loading stages L1, L2, and L3. Similar trends were observed for other analyzed parameters, including horizontal displacement for both reinforced concrete and steel sheet foundations. Additionally, Figure 5 presents a comparative analysis of stress values under the two types of foundations during backfilling. It shows that stress values in the soil under the steel foundation were consistently lower than those under the reinforced concrete foundation, even reaching a difference of 67% at load stage L3. Moreover, Depicts stress values under both foundation types during the successive application of standard loads (L1–L3), further emphasizing the superiority of the steel sheet foundation in mitigating soil stresses. These findings highlight the advantages of utilizing steel sheet foundations in terms of reduced soil stress levels and improved structural performance under various loading conditions.

Furthermore, the influence of fluid flow on ground foundation behaviour is investigated through a series of numerical simulations. By coupling fluid dynamics with structural mechanics, the methodology enables engineers to assess the impact of pore pressure variations on foundation stability and deformation. The results reveal significant changes in pore pressure distribution and foundation settlement under different hydrological conditions, highlighting the importance of considering soil-structure-fluid interaction in design and analysis. Moreover, thermal effects on ground foundation performance are examined through numerical simulations incorporating temperature-dependent material properties and thermal boundary conditions. The simulations demonstrate the significant influence of temperature variations on soil stiffness and foundation response, emphasizing the need for comprehensive thermal analyses in engineering practice.

Parametric studies are conducted to explore the sensitivity of ground foundation behaviour to key design parameters and loading conditions. By systematically varying parameters such as foundation geometry, soil properties, and loading magnitudes, engineers gain valuable insights into the factors driving system response and behaviour. Sensitivity analyses reveal critical design parameters that significantly influence foundation performance, guiding engineers in the optimization of design parameters for enhanced stability and efficiency. Additionally, the scalability and computational efficiency of the numerical modelling methodology are evaluated through simulations of large-scale ground foundation systems. The results demonstrate the capability of the methodology to handle complex geometries and loading scenarios efficiently, paving the way for its application to real-world engineering projects with confidence and reliability.

V. Discussion:

The results presented in this study underscore the effectiveness of the proposed numerical modelling simulation technology in accurately predicting the behaviour of nonlinear multi-field coupled ground foundations under diverse loading conditions. By integrating advanced computational techniques such as finite element analysis, multi-physics coupling algorithms, and advanced constitutive models, the methodology offers a comprehensive framework for simulating the complex interactions within ground foundation systems. Through detailed case studies and validation exercises, the methodology demonstrates its capability to capture the intricate phenomena of soil-structure interaction, soil-structure-fluid interaction, and thermal effects. The close agreement between simulated responses and experimental observations validates the accuracy and reliability of the numerical model, providing engineers with a powerful tool for optimizing ground foundation designs and enhancing structural performance.

Furthermore, the parametric studies conducted in this study offer valuable insights into the sensitivity of ground foundation behaviour to key design parameters and loading conditions. By systematically varying parameters such as foundation geometry, soil properties, and loading magnitudes, engineers can identify critical factors influencing foundation performance and guide the optimization of design parameters for enhanced stability and efficiency. Additionally, the scalability and computational efficiency of the numerical modelling methodology are demonstrated through simulations of large-scale ground foundation systems. The methodology proves capable of handling complex geometries and loading scenarios efficiently, underscoring its potential for application to real-world engineering projects. Overall, the discussion highlights the significance of the proposed numerical modelling simulation technology in advancing the state-of-the-art ground foundation design and analysis, fostering innovation and optimization in civil engineering practice.

VI. Conclusion:

In conclusion, this paper introduces a novel numerical modelling simulation technology tailored for the analysis of nonlinear multi-field coupled ground foundations in civil engineering applications. Through the integration of advanced computational techniques, including finite element analysis, multi-physics coupling algorithms, and advanced constitutive models, the proposed methodology offers a comprehensive framework for accurately simulating the complex interactions within ground foundation systems. Detailed case studies and validation against experimental data demonstrate the efficacy and accuracy of the numerical model, highlighting its potential to revolutionize the design and analysis of ground foundation systems. The sensitivity analyses conducted provide valuable insights into the factors influencing foundation behaviour, guiding engineers in the optimization of design parameters for enhanced stability and efficiency. Moreover, the scalability and computational efficiency of the methodology enable its application to large-scale ground foundation systems, further enhancing its practical utility in engineering practice. Overall, this paper represents a significant contribution towards advancing the state-of-the-art in numerical modelling simulation technologies for nonlinear multi-field coupled ground foundations, with implications for improving the safety, resilience, and sustainability of civil infrastructure.

VII. References

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