Research into Anchored and Non-Anchored Sheet Pile Structure under Seismic Loading Using 2D Finite Element Modzel

Duc-Trung Tran[1,*], Thanh-Xuan Trinh[1], Nguyet-Duyen Lam[2], Thi-Thuy-Phuong Nguyen[3]

[1]Civil Engineering Faculty, Can Tho University;
[2] Faculty of Engineering, Kien Giang University;
[3]Tri Viet Construction Design Consulting Company;

*Email: tdtrung@ctu.edu.vn

■Nhận bài: 20/04/2024 ■Sửa bài: 10/06/2024 ■Duyệt đăng: 20/06/2024

ABSTRACT

This study investigates the seismic performance of anchored and non-anchored sheet pile structures using a two-dimensional finite element model. Seismic loading presents a significant challenge to the stability and integrity of sheet pile walls, which are commonly used in marine, geotechnical, and civil engineering applications. By employing the finite element method (FEM), this research simulates the dynamic response of both anchored and non-anchored configurations under various seismic conditions. Key parameters such as soil-structure interaction, material properties, and boundary conditions are meticulously modelled to reflect realistic scenarios. The study aims to elucidate the differences in behavior between the two types of structures, focusing on displacements, internal forces, and potential failure mechanisms. Comparative analysis reveals the advantages and limitations of each configuration, offering insights into their suitability for different seismic intensities and soil conditions. The findings contribute to the optimization of sheet pile design, enhancing their resilience against earthquakes and informing engineering practices for safer and more reliable infrastructure development.

Keywords: *sheet pile, anchored, seismic loading*

1. Introduction

Research into anchored and non-anchored sheet pile structures under seismic loading using a 2D finite element model is a significant area of study within geotechnical engineering and earthquake engineering. Mahdi O. Karkush [1] demonstrated that a dynamic load significantly influences the sheet pile quay wall, and using additional parts of the quay wall is very useful to decrease displacements. The decrease in displacement is 49.5% and 46.5% for horizontal and vertical displacement, respectively. Sheet pile structures are commonly used in various civil engineering projects such as retaining walls, cofferdams, and bulkheads, particularly in waterfront developments and infrastructure projects.

The behaviour of these structures under seismic loading is of paramount importance due to the potential for ground shaking to induce significant lateral forces and deformations. Sheet pile structure can be separated into two major kinds: anchored and non-anchored. Anchored sheet pile structures, where the sheet piles are tied back into the ground using anchors or tie rods, exhibit different response characteristics compared to non-anchored structures, which rely solely on passive resistance and friction with the surrounding soil. The recent important improvement in computer programming provides an alternative approach method – Finite Element Method (FEM) which was used to compute the numerical model in this paper. The use of finite element modelling provides a powerful tool for analyzing the behaviour of sheet pile structures under seismic loading.

Liang Tang [2] provided useful help toward the process of safer design and more economical sheet pile walls. By discretizing the structure and surrounding soil into small elements, finite element analysis allows researchers to simulate the complex interactions between the structure, soil, and seismic forces. This enables the prediction of structural behaviour, including deformations, stresses, and failure modes, under different loading scenarios.

Key aspects of research in this area include investigating the influence of various factors such as soil properties, sheet pile geometry, anchorage design, seismic parameters, and loading characteristics on the response of sheet pile structures that have been regulated Chen, L. & Li, J.[3]. By conducting parametric studies and numerical simulations using finite element models, researchers aim to significantly improve understanding, and design some guidelines, and mitigation strategies for enhancing the seismic performance of sheet pile structures. The simulation result should be verified by the experiment data to calibrate the parameter, adjust the coefficient, debug, etc. Overall, research into anchored and non-anchored sheet pile structures under seismic loading using 2D finite element models contributes to advancing knowledge in geotechnical and earthquake engineering, ultimately leading to safer and more resilient infrastructure in seismic-prone regions. Our future work is to build up a centrifuge test model which can help to improve the accuracy of the simulated model as Bransby, M. F., & Davies, M. C. R [4-6].

2. Simulation model

Theoretical basis, Model, material and Boundary condition

The theoretical basis of researching anchored and non-anchored sheet pile structures under seismic loading using a 2D finite element model encompasses several fundamental concepts from structural dynamics, soil mechanics, and finite element analysis. Here are the key theoretical components: Structural Dynamics: we can understand the characteristics of seismic waves and their interaction with structures. Seismic loading is often represented by acceleration time histories that simulate real earthquake events. Analysis of how structures respond to dynamic loads, including natural frequencies, mode shapes, and damping effects [7-9].

Soil Mechanics: Examining how the soil and structure interact under seismic loads. This involves understanding the behavior of soil under dynamic loading, including aspects such as the stiffness of soil, damping, and potential liquefaction. Implementing appropriate soil models (Mohr-Coulomb, Drucker-Prager) that capture the non-linear and inelastic behavior of soil during seismic events [10].

Sheet Pile Structures: Fundamental principles of sheet pile wall design, including the types of forces they are subjected to and how they resist these forces. Distinguishing between anchored sheet pile walls, which use tiebacks or anchors to provide additional stability, and non-anchored walls, which rely solely on their embedment in the soil for stability [11].

Finite Element Method (FEM): Creating a two-dimensional representation of the sheet pile structure and surrounding soil. This involves discretizing the domain into elements and applying the governing equations of motion. Material Properties and Boundary Conditions: Defining the main material properties for both soil and sheet piles, and we can set appropriate boundary conditions to simulate some realistic scenarios. Utilizing numerical methods to solve the equations of motion, such as time-stepping algorithms for dynamic analysis [12].

Analysis and Comparison: Identifying key performance indicators such as displacements, bending moments, shear forces, and stress distribution of the structure. Pitilakis, K. [13] provides methodologies for comparing the seismic performance of different types of retaining structures, including sheet pile walls. We can compare the behavior of anchored and non-anchored sheet piles under identical seismic loading to determine their relative advantages and drawbacks.

Failure Mechanisms: Investigating possible failure mechanisms such as bending failure, shear failure, and overall instability. Assessing the safety and resilience of each configuration, providing insights into their effectiveness in withstanding seismic events [14].

By integrating these theoretical foundations, the research aims to provide a comprehensive understanding of how anchored and non-anchored sheet pile structures perform under seismic loading, thereby informing better design practices and enhancing the safety and reliability of such structures in seismic-prone areas.

Our simulation model is a series of sheet piles connected by a steel beam, embedded in a sandy ground. The model sheet pile exhibited a stiffness (EI) of 5.10^3 kNm. There were Young's modulus and the moment of inertia of the sheet pile, respectively. In this case, I created two different sheet pile wall structures, one was anchored to the ground with an embedment depth was 2.2 meters, and another one was installed 5.2 meters into the ground without anchor. A fine quartz sand (D_{50}) = 0.193 mm; D_{10} = 0.147 mm; internal friction angle (IFA) = 37^o at relative density (Dr) = 50%; cohesive (c) = 0 kPa; Elastic Young modulus = 50 MPa, Damping ratio = 0.1; Poisson ratio = 0.33) was used to create the uniform deposit.

Young's modulus of the sheet pile material is a crucial parameter in analyzing the behaviour of sheet pile structures under various loading conditions, including seismic loading. Young's modulus, often denoted by E, represents the stiffness or rigidity of the material and quantifies its resistance to deformation under stress. The value of Young's modulus for sheet pile materials can vary depending on the type of material used. Common materials for sheet piles include steel, concrete, and composite materials. Each material has its own Young's modulus value, which can be determined through laboratory testing or referenced from material specifications. For example: Steel sheet piles typically have a Young's modulus ranging from 190 to 210 GPa. Concrete sheet piles may have Young's modulus in the range of 20 to 40 GPa, depending on factors such as concrete mix design and curing conditions. Composite sheet pile materials, which combine different materials such as fibreglass and resin, can have Young's modulus values that fall within a specific range determined by their composition and manufacturing process. In finite element modelling and structural analysis of sheet pile structures, the accurate determination of Young's modulus is essential for predicting deflections, stresses, and overall structural behaviour. Therefore, it is important to use appropriate material properties based on the specific type of sheet pile being analyzed. These properties can be obtained from material datasheets, standards, or experimental testing.

The internal friction angle, often denoted by the symbol ϕ, is a fundamental parameter in geotechnical engineering that characterizes the shear strength of soils. It represents the resistance of soil particles to sliding along internal planes when subjected to shear stresses.

The internal friction angle is typically determined through laboratory tests, such as the direct shear test or the triaxial shear test, where soil samples are subjected to controlled loading conditions to measure their shear strength properties. In the context of sheet pile structures, the internal friction angle of the soil surrounding the sheet pile is an important factor in analyzing the lateral earth pressure exerted on the sheet pile and its overall stability. It influences the magnitude of lateral earth pressure, which in turn affects the design of sheet pile walls, especially in retaining wall applications. Different types of soils exhibit varying internal friction angles due to their particle characteristics, such as size, shape, and angularity. For example: Cohesive soils, such as clay, typically have low internal friction angles, ranging from about 0 to 30 degrees. Granular soils, such as sand and gravel, generally have higher internal friction angles, typically ranging from 30 to 45 degrees. In numerical analyses and design calculations involving sheet pile structures, the internal friction angle of the surrounding soil is considered along with other soil parameters to accurately model soil-structure interaction and determine the stability and performance of the sheet pile wall under various loading conditions, including seismic loading.

Relative density, often denoted by the symbol Dr, is a measure used in geotechnical engineering to quantify the degree of packing or denseness of soil or granular materials relative to their maximum and minimum possible densities. In simpler terms, relative density indicates how densely packed the soil particles are compared to the densest possible arrangement (100% relative density) and the loosest possible arrangement (0% relative density). For granular soils, such as sand and gravel, relative density is commonly used to characterize their compaction state and shear strength. Higher relative densities typically correspond to greater particle interlock and increased shear strength, while lower relative densities indicate looser, more open structures with lower shear strength. Relative density is often determined through field tests or laboratory experiments, such as the standard Proctor compaction test or the modified Proctor compaction test, where soil samples are subjected to controlled compaction efforts to assess their density and void ratio n, in the context of sheet pile structures, the relative density of the soil surrounding the sheet pile can influence parameters such as lateral earth pressure, soil-structure interaction, and overall stability. Understanding the relative density of the soil is essential for the accurate design and analysis of sheet pile walls, particularly in applications where soil compaction and shear strength are critical factors.

In control systems, the damping ratio affects the stability and responsiveness of the system. For buildings and bridges, the damping ratio is crucial for understanding how structures will respond to dynamic loads like wind or earthquakes. The damping ratio (ζ) is a key parameter used to describe the damping characteristics of a dynamic system. In the context of structural dynamics, including seismic analysis, the damping ratio quantifies the level of damping present in a structure relative to its critical damping. Damping is a dissipative mechanism that reduces the amplitude of vibrations or oscillations in a system over time. It represents the energy dissipation per cycle of vibration. The critical damping coefficient represents the minimum amount of damping required to prevent oscillations in a system. When the damping ratio is less than 1 (ζ<1), the system is considered underdamped, and oscillations occur, and when the damping ratio is equal to 1 (ζ=1), the system is critically damped, resulting in the fastest possible decay of oscillations without overshooting. In structural dynamics and earthquake engineering, the damping ratio is a critical parameter in analyzing the response of structures to dynamic loads, including seismic loading. It influences the amplitude, duration, and frequency content of structural vibrations, as well as the structural response and overall performance during earthquakes. Determining an appropriate damping ratio for a given structure and loading condition is essential for accurate seismic analysis and design.

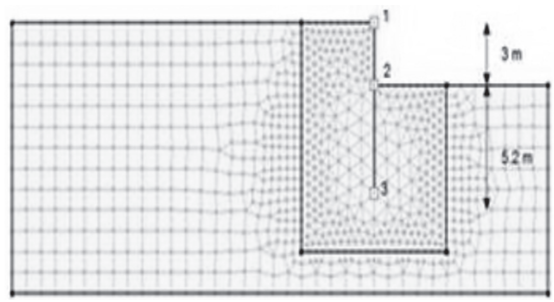

Fig 1. *The non-achored sheet pile structure*

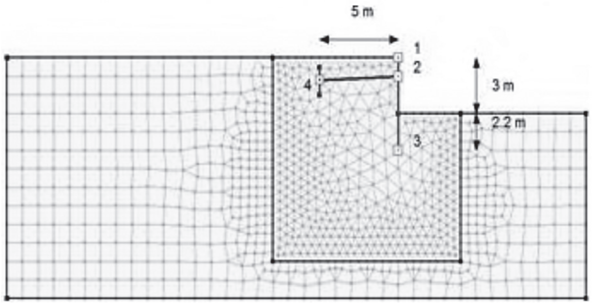

***Fig 2.** The anchored sheet pile structure*

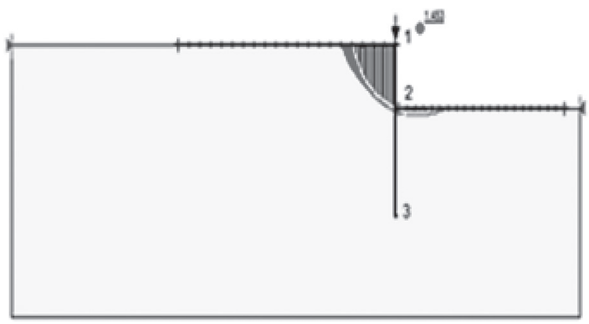

***Fig 3.** The critical slip surface of anchored system*

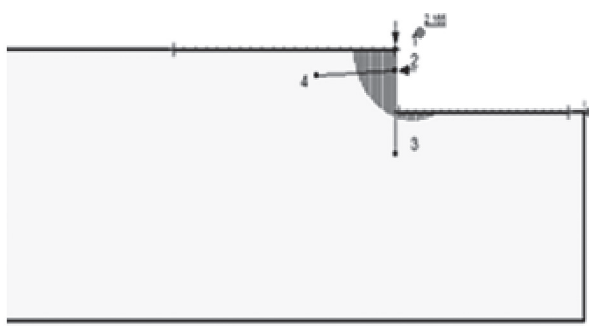

***Fig 4.** The critical slip surface of non-anchored system*

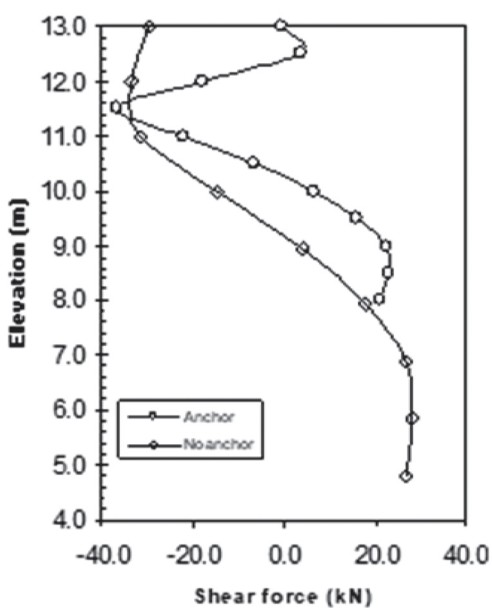

***Fig 5.** Shear force vs. elevation*

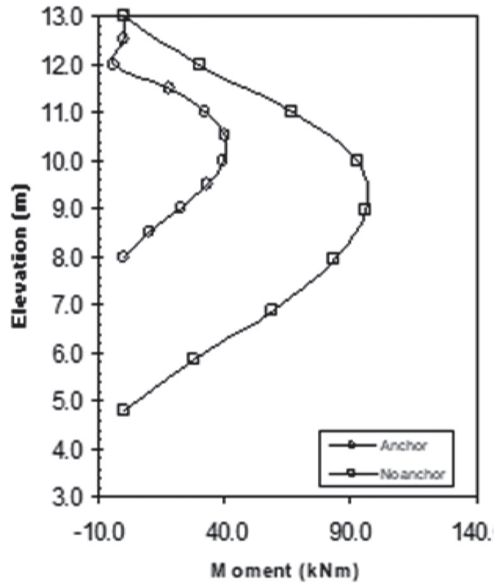

***Fig 6.** Moment vs. elevation*

Both systems were designed in the current design code (Blum method) to reach a stable state. At static conditions, the factor of safety of the sheet pile system with the anchor was 2.165 and the other one was 1.453. The critical slip surface of each model was recorded to analyze in shaking event by the Newmark method. The moment and shear force distribution along the depth of the sheet pile are shown in Fig. 5 and Fig. 6

The Blum Method is a widely used approach in geotechnical engineering for estimating the lateral earth pressure acting on retaining structures, such as sheet pile walls, in cohesive soils. It was developed by Karl von Terzaghi and Otto Blum and is based on the assumption that the lateral earth pressure distribution is linear, with the pressure increasing linearly with depth [15]

The Blum Method provides a simplified yet practical way to estimate the lateral earth pressure distribution, especially in cohesive soils where the pressure distribution can be more complex than in granular soils. The basic steps of the Blum Method are as follows: Calculate Active Earth Pressure Coefficient: K_a using either analytical methods or empirical relationships. and the height of the retaining wall to estimate the lateral earth pressure (P) at different depths.

The point 1 to 4 in Fig.2 and 1 to 3 in

Fig.1 denoted the point that we are interested in further discussion. The bottom of the sand layer was assigned a hinge boundary condition (the displacement in both X and Y directions equal to zero). Aside from the model, zero X-displacement conditions were applied at the initial stress analysis, and fixed Y-displacement conditions were assigned in the shaking event

The term "shaking event" typically refers to the ground shaking caused by an earthquake. During an earthquake, the Earth's crust experiences a sudden release of accumulated energy, resulting in seismic waves that propagate through the Earth. These seismic waves cause the ground to shake, which can result in varying degrees of damage to structures, infrastructure, and the natural environment. The intensity and duration of ground shaking during an earthquake depend on several factors, including the magnitude and depth of the earthquake, the distance from the epicentre, the local geology and soil conditions, and the propagation path of the seismic waves. Understanding the characteristics of ground shaking is crucial in earthquake engineering and seismic hazard assessment. Engineers analyze ground shaking data to assess the potential impact on structures and infrastructure, evaluate the seismic vulnerability of buildings and other facilities, and design earthquake-resistant structures to mitigate the effects of ground shaking. Seismic shaking events are typically described using various parameters, including the earthquake magnitude, peak ground acceleration (PGA), peak ground velocity (PGV), and spectral acceleration. These parameters help quantify the intensity and severity of ground shaking and inform engineering decisions related to seismic design and risk mitigation strategies.

3. Shaking event :

These two models are subjected to seismic loading as a sine wave (peak acceleration = 0.2g, duration = 6.0s). The sine wave input quickening history is available for calibrating the simulation result by shaking the table. Based on the obtained parameter we computed the model by using commercial FEM analysis software – GeoStudio 11.3

The sine wave, often simply referred to as the sine function or sinusoid, is a fundamental mathematical function that describes a smooth, repetitive oscillation.

4. Simulation result:

The anchored system simulation result could encompass various outcomes depending on the specific parameters and context of the simulation, example : structural stability, displacement analysis, Stress Distribution, Dynamic Response, Failure Points, Fatigue Life.

The anchored system

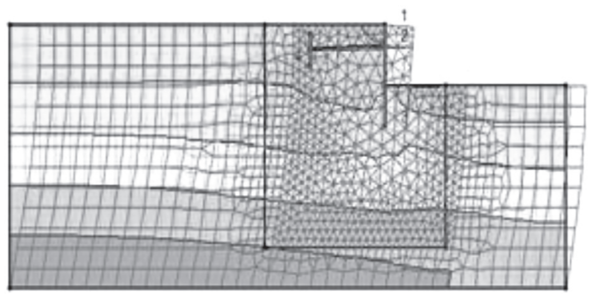

Fig 7. *Relative deformation mesh and Sine wave vs. time*

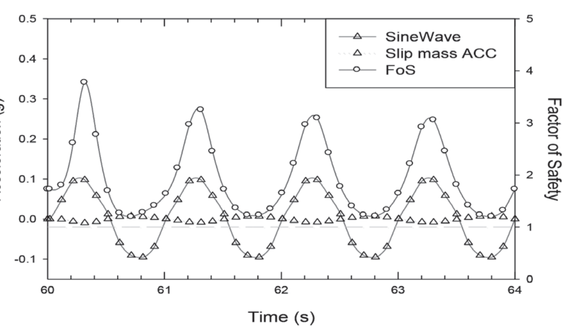

Fig 8. *The Factor of safety, acceleration mass*

The non-anchored system

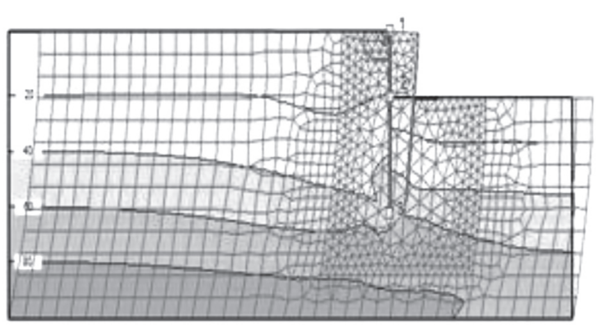

Fig 9. *Relative deformation mesh*

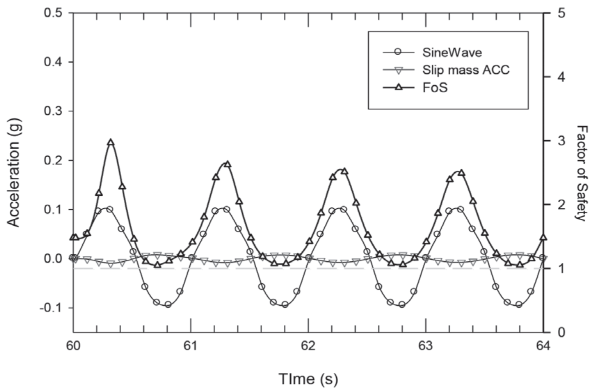

Fig 10. *The FoS, acceleration mass and Sine wave vs. time*

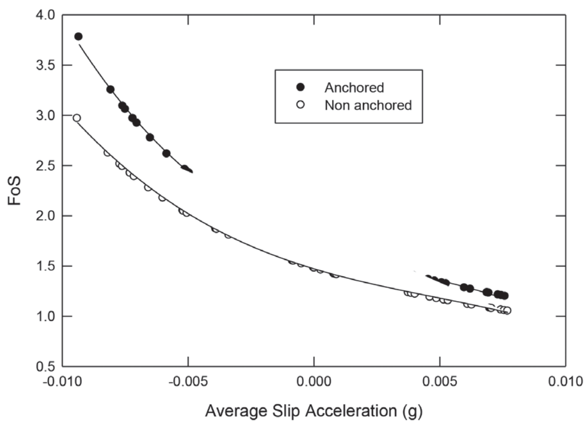

Fig 1*1. FoS vs. average slip acceleration*

5. Discussion

Research into anchored and non-anchored sheet pile structures under seismic loading using 2D finite element models presents a significant and multifaceted area of study within geotechnical and earthquake engineering. This topic offers numerous avenues for exploration and discussion, encompassing various aspects of structural behaviour, soil-structure interaction, and seismic performance. Here are some potential discussion points:

- As shown in Fig. 8 and Fig.10, the anchored system has a higher FoS than the non-anchored system in the same base shaking domain

- Analysis Techniques: Discuss the improtant methodologies and techniques employed in modelling anchored and non-anchored sheet pile structures using 2D finite element models. Highlight the advantages and limitations of finite element analysis in capturing the complex interactions between the structure, soil, and seismic forces.

- Effect of Anchorage: Compare and contrast the behaviour of anchored and non-anchored sheet pile structures under seismic loading. Explore how the presence of anchors or tiebacks influences factors such as lateral displacement, bending moments, and overall stability during seismic events as we discussed above, the factor of safety increases whenever the acceleration of the slip mass decreases.

- Soil-Structure Interaction: Examine the role of soil properties, including soil stiffness, strength, and damping, in governing the response of sheet pile structures to seismic loading. Discuss how variations in soil conditions impact the dynamic behaviour and performance of anchored and non-anchored sheet pile walls

- Seismic Design Considerations: Discuss the seismic design criteria and guidelines applicable to sheet pile structures in seismic-prone regions. Address key considerations such as seismic loading parameters, design acceleration spectra, and performance objectives (e.g., allowable deformations, and structural integrity).

- Mitigation Strategies: Explore potential mitigation strategies for enhancing the seismic resilience of sheet pile structures. This may include the use of innovative anchorage systems, soil improvement techniques, or structural reinforcement methods to mitigate the effects of seismic loading and improve overall performance.

- Validation and Verification: Discuss the importance of validation and verification of finite element models through comparison with experimental data or field observations. Highlight the challenges and best practices in validating numerical simulations of sheet pile structures under seismic loading.

- Case Studies: Present case studies or

real-world examples of sheet pile structures subjected to seismic loading events. Analyze the performance of these structures, lessons learned, and implications for future design and construction practices.

● Future Research Directions: Identify emerging research trends and areas for further investigation in the field of anchored and non-anchored sheet pile structures under seismic loading. Discuss potential avenues for advancing numerical modelling techniques, improving seismic design methodologies, and enhancing the resilience of sheet pile infrastructure

By delving into these discussion points, researchers and practitioners can gain deeper insights into the behaviour and performance of sheet pile structures under seismic loading, ultimately contributing to the development of more robust and resilient engineering solutions.

6. Conclusion

The research on anchored and non-anchored sheet pile structures under seismic loading using a 2D finite element model yields significant insights into their dynamic behavior and performance. The study demonstrates that anchored sheet pile walls exhibit enhanced stability and reduced displacements compared to non-anchored walls, owing to the additional restraint provided by the anchors. This added stability is crucial in mitigating the adverse effects of seismic forces, particularly in regions prone to high-intensity earthquakes.

Conversely, non-anchored sheet pile structures, while simpler and potentially more cost-effective, show greater susceptibility to large displacements and potential failure under seismic loading. The finite element analysis highlights critical stress points and deformation patterns that can inform improved design and construction practices.

Overall, the comparative analysis underscores the importance of considering site-specific seismic conditions and soil characteristics when choosing between anchored and non-anchored configurations. The findings advocate for the use of anchored sheet piles in high-risk areas to ensure structural integrity and safety. This research contributes to the field by providing a detailed assessment of seismic performance, guiding engineers in optimizing sheet pile designs for enhanced earthquake resilience. Future work could expand on this foundation by incorporating three-dimensional modeling and exploring a broader range of seismic scenarios and soil conditions.

References

[1] Mahdi O. Karkush, Shahad D. Ali, Naghm M. Saidik , Alaa N. Al-Delfee (2022), "Numerical Modeling of Sheet Pile Quay Wall Performance Subjected to Earthquake", Geotechnical Engineering and Sustainable Construction. Springer

[2] Liang Tang (2018), "Finite element analysis of lateral earth pressure on sheet pile walls", *Harbin Institute of Technology.* Elsevier

[3] Chen, L., & Li, J.(2019), "Influence of Soil Parameters on the Behavior of Sheet Pile Walls under Seismic Loading ", *Journal of Geotechnical and Geoenvironmental Engineering, 145(5), 04019018.*

[4] Bransby, M. F., & Davies, M. C. R. (2000). "Centrifuge Modeling of Caisson Foundations for Offshore Structures." *International Journal of Physical Modelling in Geotechnics*, 1(1), 1-13. DOI:10.1680/ijpmg.2000.020100

[5] Elgamal, A., & Lu, J. (2009). "Seismic Performance of Sheet Pile Anchorage Systems." *Journal of Earthquake Engineering*, 13(4), 526-542. DOI:10.1080/13632460902868122.

[6] Hushmand, B., Scott, R. F., & Crouse, C. B. (1988). "Centrifuge Modeling of Seismic Soil-Structure Interaction." Journal of Geotechnical Engineering, 114(8), 903-921.

[7] Boore, D. M., & Joyner, W. B. (1997). "Site Amplifications for Generic Rock Sites."

Bulletin of the Seismological Society of America, 87(2), 327-341

[8] Chopra, A. K. (2017), Dynamics of Structures: Theory and Applications to Earthquake Engineering (5th ed.). Pearson

[9] Hart, G. C., & Wong, K. (2000), "Structural Dynamics for Structural Engineers", Wiley.

[10] Vucetic, M., & Dobry, R. (1991). "Effect of Soil Plasticity on Cyclic Response." Journal of Geotechnical Engineering, 117(1), 89-107. DOI:10.1061/(ASCE)0733-9410(1991)117:1(89).

[11] Terzaghi, K., Peck, R. B., & Mesri, G. (1996), " *Soil Mechanics in Engineering Practice* (3rd ed.)", Wiley

[12] Hsieh PG, Ou CY.(1998), "Shape of ground surface settlement profiles caused by excavation", *Can Geotech J 35(6)*, pp:17 -64.

[13] Pitilakis, K. (2016), "Seismic Analysis and Design of Retaining Structures, Buried Structures, Slopes, and Embankments." In: Geotechnical Earthquake Engineering Handbook. Springer

[14] Kramer, S. L. (1996), " *Geotechnical Earthquake Engineering",* Prentice Hall.

[15] Terzaghi, K., & Peck, R. B. (1967). Soil Mechanics in Engineering Practice (2nd ed.). Wiley

[16] Wald, D. J., Quitoriano, V., Heaton, T. H., & Kanamori, H. (1999). "Relationships Between Peak Ground Acceleration, Peak Ground Velocity, and Modified Mercalli Intensity in California." Earthquake Spectra, 15(3), 557-564. DOI:10.1193/1.1586058

[17] Konda T, Ota H, Yanagawa T, Hashimoto A. (2008), "Measurements of ground deformations behind braced excavations", *the 6th international symposium on geotechnical aspects of underground construction in soft ground*; p p: 295–300.

[18] Long M. (2001), "Database for retaining wall and ground movements due to deep excavations", J Geotech Geoenviron Eng 127(3), pp: 203–24.

[19] Liao JT, Ou CY (1997), "Engineering performance of a deep excavation of Taipei National Enterprise Centre, research report GT 96008" *National Taiwan University of Science and Technology* [in Chinese].

[20] Liu GB, Ng CWW, Wang ZW (2005) "Observed performance of a deep multistructured excavation in Shanghai soft clays", *J Geotech Geoenviron Eng 131(8), pp:* 13-104.

[21] Lin HD, Ou CY, Wang CC (2002) "Time-dependent displacement of diaphragm wall induced by soil creep", *J Chinese Inst Eng 25(2),* pp: 223–31.

[23] Wallace JC, Ho CE, Long M. (1992), " Retaining wall behaviour for a deep basement in Singapore marine clay", Proceedings of the International Conference on Retaining Structures. London, pp. 195–204

[24] Lu CC (2006), " *Numerical analysis of deep excavation in soft ground*", MSc thesis, National Kaohsiung University of Applied Sciences, Taiwan.

[25] Mair RJ.(1993), "Unwin memorial lecture -Developments in geotechnical engineering research: application to tunnels and deep excavations", *Proc Inst Civ Eng, Civ Eng, pp*: 27–41.

[26] W.P. Dawkins (2001), "Investigation of wall friction, surcharge loads, and moment reduction curves for anchored sheet pile walls", *US Army Corps of Engineers, ERDC/ITL.*

[27] L. Grande, O.K. Soreide, T.H. Tefera (2002), "Large scale model testing on the moment distribution and deformation behavior of a sheet pile wall", *in 2nd International Conference on Soil Structure Interaction in Urban Civil Engineering, Zurich, Switzerland*, pp. 389–394.

[28] N. Kumar, A. Dey (2014), " Behavior of Rigid Cantilever Sheet Pile Walls: Numerical and Finite Element Analysis", *Indian Geotechnical Conference, Netherlands*, pp. 18–20.