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PID Control System for Shaking Table and Bearing Capacity Measurement on Soil Liquefaction Simulator

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ABSTRACT

Liquefaction occurs when previously stable soil suddenly loses its strength and stiffness due to seismic excitation, resulting in severe damage to foundations and structures. This study presents the development of a 1-g shaking-table system designed to simulate and evaluate soil liquefaction and foundation performance under controlled vibration. The system, implemented using LabVIEW, enables real-time measurement and analysis of soil behavior before, during, and after simulated earthquakes, while accounting for the influence of foundation reinforcement. A PID control algorithm was applied and tuned using the Ziegler–Nichols (ZN) method to enhance control accuracy and stability during seismic vibration testing. The ZN-tuned system achieved a rise time of 8 s, delay time of 13 s, overshoot of 0.06 %, settling time of 13 s, and a steady-state error of 0.02 %. When compared with the Trial-and-Error (TE) method, the ZN approach provided faster rise, delay, and settling times but resulted in slightly higher overshoot and steady-state error. Sensor data from the strain-gauge load cell indicated that the helical-pile foundation sustained an average bearing capacity of 3.99 kPa, confirming its ability to support vertical loads during liquefaction. Overall, the experimental results validate the effectiveness of the PID-controlled shaking-table system for investigating soil–structure interaction during liquefaction. The proposed setup offers an accurate and efficient platform for assessing foundation stability, improving structural resilience, and mitigating the risks associated with seismic-induced ground failure.

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1. Introduction

Due to its location near the meeting point of four major tectonic plates — the Eurasian, Indo-Australian, Pacific, and Philippine plates — a large portion of Indonesia is subject to frequent earthquakes. The 2018 Palu earthquake, one of the strongest in Indonesia that year, was a stark example of this. The 7.4-magnitude quake left widespread devastation and many dead, mostly in Palu and Donggala cities. It also caused liquefaction, which made the ground unstable and shifted resulting in the massive destruction of homes and infrastructure. Tragically, many people were buried alive as a result of the earthquake. It was difficult to collaborate with local authorities because of the disruptions to communication that occurred in the impacted areas [1]. Palu's liquefaction claimed 1,703 lives, bringing the death toll from the incident to 2,113. In addition, 223,751 individuals were displaced and evacuated to 122 locations, while 4,612 persons sustained injuries. Physical damage totaled Rp 15.58 trillion, while economic damage was estimated at Rp 2.89 trillion. There have been liquefaction incidents in Indonesia previously, including in 1971 when the San Fernando earthquake damaged a dam [1]. As a result, building plans in Indonesia need to take into consideration the possibility of ground failure, which could have an effect on the structures, in addition to structural failures [2].

Liquefaction is a phenomenon where a soil which previously stable suddenly loses its strength in a short period of time. When there is an earthquake, the shear forces generated cause the shifting of sand or soil grains, which increases the water pressure in the pores of the soil. As a result of these rapid cyclic vibrations, the soil loses most of its strength and stiffness, so it is no longer able to support the structures above it or maintain stability [3]. Liquefaction can also cause damage to infrastructure such as roads, buildings and underground pipes, which can disrupt daily activities and require large repair costs [10]. Buildings on soil subjected to liquefaction may tilt or even collapse because the soil loses its strength that was previously able to support the building stably [4-6].

Without adequate foundations, a building can experience gradual settlement, tilting, or total collapse during or after liquefaction, posing a high risk of hazardous situations for occupants or the surrounding environment. The use of reinforcement in the lower structure of a building can minimize the impact caused by liquefaction. One type of the reinforcement is Helical pile which has a function to increase the soil bearing capacity that has liquefaction potential [7].

One of the methods used to simulate liquefaction is by using a shaking table, a device capable of replicating ground vibration caused by earthquake on a laboratory scale. Shaking tables allow researchers to conduct dynamic testing of soil models and overlying structures, and directly observe how water-saturated soil responds to the vibrations. However, the effectiveness of a shaking table is highly dependent on the control system used. A good control system will ensure that the vibrations generated match the desired earthquake scenario, making the test results more accurate and representative.

In addition, the ability to measure the bearing capacity of soil during liquefaction tests is critical in analyzing the feasibility of foundations. Bearing capacity measures how much load can a soil support before it reaches failure. Under liquefaction conditions, the bearing capacity of the soil tends to decrease dramatically, which potentially causing the collapse of the structures over it. Therefore, a measurement system integrated with a shaking table is required to monitor changes in bearing capacity during testing. In another research titled "An Experimental Evaluation of Helical Piles as a Liquefaction-Induced Building Settlement Mitigation Measure, 2021," the main focus was to evaluate the use of helix pile to reduce settlement and slope of buildings as a result of liquefaction. The sensors used in the research are similar to this research, which uses accelerometer and strain gauge sensors[11-12]. The strain gauge sensor serves to measure the bearing capacity of the reinforced foundation. The difference lies in the shaking table control input; the study used the displacement value of the string potentiometer, while in this study, the shaking table control is done based on the frequency of the accelerometer sensor input [8].

This research shows that liquefaction is a dangerous phenomenon that requires special attention in its mitigation efforts, one of which is the use of test equipment such as Helical pile foundation reinforcement and sensor-based monitoring technologies such as accelerometers and strain gauges. This approach not only measures the bearing capacity of the soil, but also provides accurate data for earthquake analysis and control. Therefore, research which focused on the development of a liquefaction simulator tool based on LABVIEW can give a significant contribution in reducing liquefaction impacts and improving building safety in areas which are prone to earthquake. This initiative is an important step in strengthening infrastructure resilience and protecting communities from natural disasters potential.

2. Method

This research was conducted at the Civil Engineering Soils Laboratory, Politeknik Negeri Jakarta. This location was chosen because the laboratory provides a controlled and safe environment, which allows the experiments to be conducted with high accuracy and precision. In this setting, researchers can replicate experiments under various soil conditions and earthquake intensities, and utilize advanced technology for detailed measurement and data analysis. In addition, this research provides opportunities for learning and scientific development, and enables small-scale simulations that are more efficient and economical than field experiments.

This research developed a model of soil liquefaction test equipment using a 1-g shaking table as shown in Fig. 2. This tool consists of a 40 x 40 x 50 cm box containing replicas of buildings, soil and foundations, and is equipped with a motor to simulate an earthquake, or shaking table. The shaking motion is regulated by an inverter based on a certain frequency that is adjusted to the scale of the simulated earthquake. The system is designed to analyze soil characteristics before, during, and after an earthquake that causes liquefaction with foundation reinforcement. The aim is to identify measures that can be taken to reduce the impact of liquefaction on the soil.

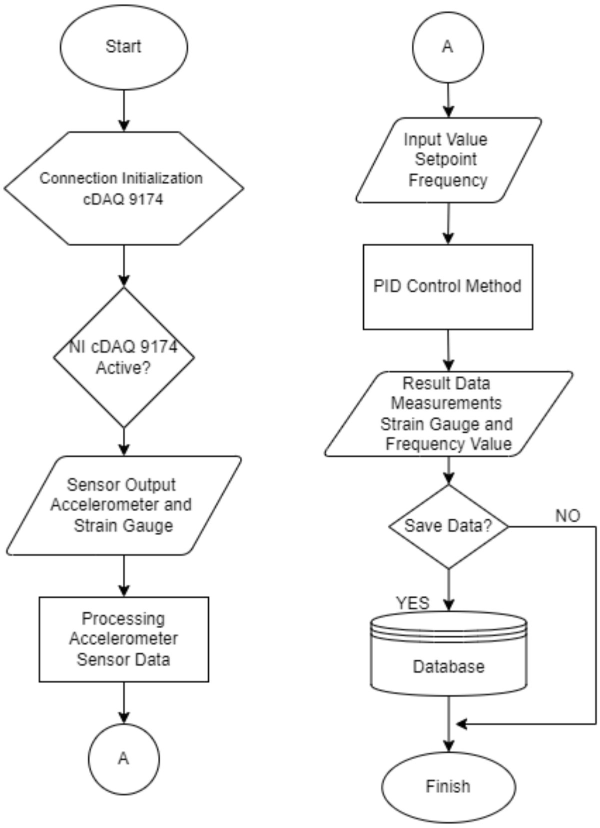

Fig.1. System Flowchart

As shown in Fig. 1, When starting the research, the system initializes the connection of the cDAQ 9174, if it is not connected it will return to initialize. If the NI cDAQ 9174 is already active, it will read the output of the strain gauge and Accelerometer sensor which will then be processed data on the Accelorometer sensor. Next, input the frequency setpoint value which will be continued with the PID control method. If the PID control method has been running, the strain gauge measurement data and frequency values will appear on the HMI display which will then be stored in the database.

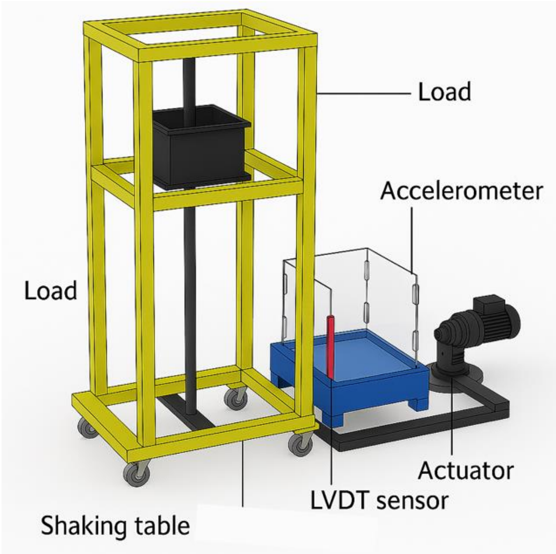

Fig.2. Design of the shaking table apparatus

A strain gauge sensor is used to measure the foundation bearing capacity, ensuring that the foundation can withstand the applied load. Bearing capacity was measured using a load cell placed beneath the soil container. The output force (F) was divided by the contact area (A) of the foundation plate to calculate the ultimate bearing pressure (q = F/A). On the other hand, accelerometer measures the acceleration and frequency of vibration, giving critical information about the structure's response to vibration, just as what occurs on the shaking-table experiment. The data combination from these sensors gives a comprehensive picture of the soil conditions and the structure stability.

In this study, the Ziegler-Nichols method is used to tune the PID control in a shaking table system to achieve optimal control performance. The tuning process begins by identifying two important parameters: the delay time (L) and the rise time (T) of the system response to an input signal. The first step in this method is to apply a stepwise input is to the system and observe it, focusing mainly on the delay time (L) and rise time (T). The delay time refers to the period required for the system to start responding after the input is applied, while the rise time is the duration required for the system to reach 63.2% of its final value after the response begins. Once L and T are determined, the PID parameters are calculated using the Ziegler-Nichols formula, which is adapted for P, PI, and PID controllers. These parameters are then implemented into the PID control system on the shaking table to regulate the dynamic response, ensuring the system can reproduce the desired vibration pattern with high accuracy and sufficient stability during testing. Table 1 shows the Ziegler Nichols tunning method.

Table 1. Table of Tunning Ziegler Nichols Ordo 1

Controller	K_p	T_i	T_d
P	$\frac{T}{L}$	∞	0
PI	$0.9\frac{T}{L}$	$\frac{T}{0.3}$	0
PID	$1.2\frac{T}{L}$	2L	0.5L

The Process Reaction Curve method is used to identify the graphical response characteristics or curves of a system. This response curve, as shown in Fig. 3, is the result of the system responding to a step function change in several measurable parameters. Based on the graph, the system parameters are obtained to determine the Process Reaction Curve equation.

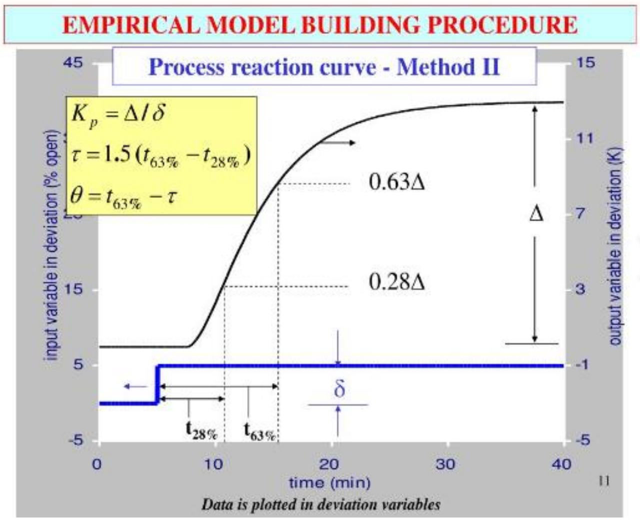

Fig. 3. Process Reaction Curve Graph

The Process Reaction Curve calculation equations are as follows

$$K_p = \frac{\Delta}{\delta} \quad (1)$$

$$63\% \, \Delta = \Delta \, (0.63)$$

$$28\% \, \Delta = \Delta \, (0.28)$$

$$\mathrm{T} = 1.5 \, (t_{63\%} - t_{28\%}) \quad (2)$$

$$\mathrm{L} = t_{63\%} - T$$

$$Gp(s) = \frac{K_p}{\mathrm{T}(s)+1} \, e^{-Ls} \quad (3)$$

3. Results and Discussion

Based on the design and experiments carried out in the Civil Engineering Laboratory at Politeknik Negeri Jakarta, as illustrated in Fig. 4, the 1-g shaking table model was created using hebel blocks measuring 19.5 x 19.5 x 10 cm (L x W x H) to represent a building structure. Data for the research were gathered from various sensors, including accelerometers and strain gauges.

In this study, a helical pile measuring 220 cm in length and 4 cm in diameter was utilized, designed to transfer the load from the building to deeper, more stable soil layers, ensuring the structure's stability and optimal bearing capacity. The helical pile was installed by screwing it into the ground, similar to installing a screw, which allowed for quick installation and minimized disruption to the surrounding environment.

Fig 4. Shaking Table Design

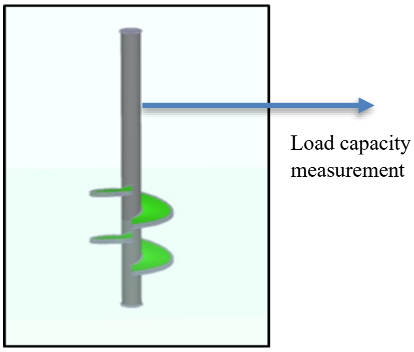

Fig. 5. Helical Pile Design

Fig. 6. HMI LabVIEW Visualization

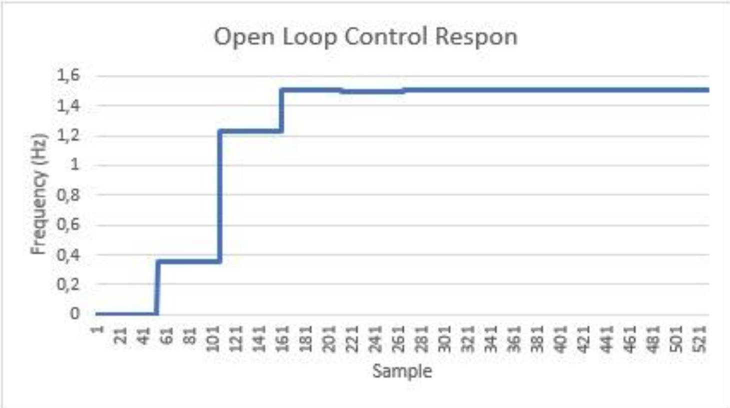

Fig. 7. Response of Open Loop System

In the LabVIEW system, the Human-Machine Interface (HMI) is essential for displaying measurement data during tests, making it easier for users to monitor and analyze information through a clear and informative interface. As illustrated in Fig. 6, the HMI includes various buttons to assist with testing, indicators showing the measured data, and graphs that present the results from each sensor being tested.The PID control method is employed to manage the shaking table's vibration frequency at 1.2 Hz over a period of 30 seconds, using the Ziegler-Nichols tuning approach. The vibration frequency of 1.2 Hz was selected based on the dominant frequency range of low-intensity seismic events affecting shallow foundations, corresponding to the natural frequency of the soil–structure system. The following outlines the design for PID tuning. Based on Fig. 7, the mathematical modeling of the control system for the shaking table can be designed using the following equations:

$$\Delta PV = \max output\ value - \min output\ value \quad (4)$$

$$\Delta PV = 1.5 - 1 = 0.5$$

$$\delta = \max input\ value - \min input\ value \quad (5)$$

$$\delta = 1 - 0 = 1$$

The static gain value for the system is then determined as follows.

$$K = \frac{\Delta}{\delta} = \frac{1.5}{1} = 1.5$$

Next, the values of the constants T T and L L are determined based on the 63 % 63% value of $P\ V$ PV from the initial steady state, as follows:

$$PV_{63\%} = 0{,}63\ (\ \Delta PV)$$

$$PV_{63\%} = 0{,}63\ x\ 1.5 = 0{,}945$$

$$t_{63\%} = 11\ s$$

$$PV_{28\%} = 0{,}28\ (\ \Delta PV)$$

$$PV_{28\%} = 0{,}28\ x\ 1{,}4 = 0{,}42$$

$$t_{28\%} = 6\ s$$

$$T = 1{,}5\,(t_{63\%} - t_{28\%})$$
$$T = 1{,}5\,(11 - 6) = 5$$
$$T = 5\ \mathrm{s}$$
$$L = t_{63\%} - T$$
$$L = 11 - 5$$
$$L = 6\ \mathrm{s}$$

The calculations result in $T = 5$ and $L = 6$. Therefore, the PID control can be modeled using the Ziegler-Nichols first-order method, as illustrated in Table 1. The PID tuning table is provided below.

$$Kp = 1{,}2\,\frac{\tau}{l}$$
$$Kp = 1{,}2\left(\frac{5}{6}\right) = 1$$
$$Ti = 2l$$
$$Ti = 2\,x\,6 = 12$$
$$Td = 0.5l$$
$$Td = 0{,}5\,x\,6 = 3$$

The results of the PID control testing on the shaking table, set to a frequency of 1.2 Hz for 30 seconds using the Ziegler-Nichols method with parameters $Kp = 1$, $Ti = 12$, and $Td = 3$, can be seen in Fig. 8 and Fig. 10.

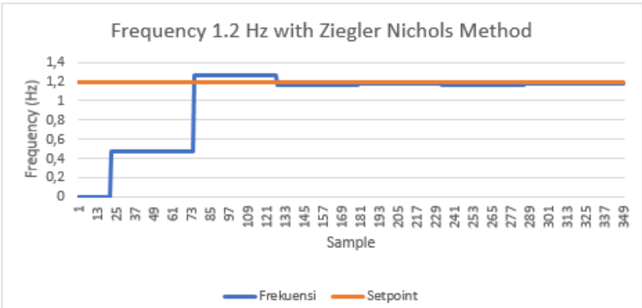

Fig. 8. Ziegler-Nichols System Response Graph method

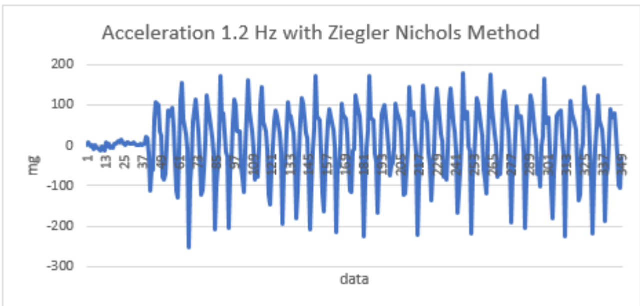

Fig. 9. Ziegler Nichols method Acceleration Graph

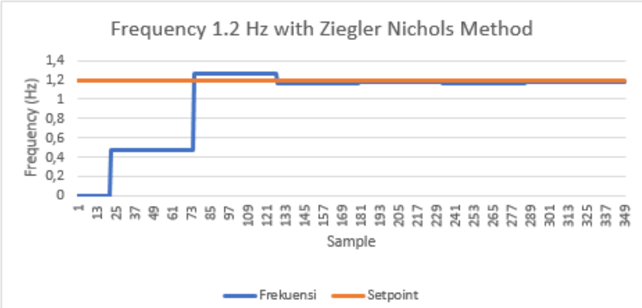

Fig. 10. System Response Graph Trial and Error Method

Fig. 8 and Fig.10 illustrate the system response of the shaking table tuned using two different PID parameter sets: the Ziegler–Nichols (ZN) and Trial-and-Error (TE) methods. The target excitation frequency was 1.2 Hz, and both tuning schemes successfully achieved steady-state tracking; however, their transient characteristics differed significantly. Using the ZN parameters (Kp = 1, Ti=12, and Td=3), the system achieved a rise time of 8 s, a delay time of 13 s, a settling time of 13 s, an overshoot of 0.06 %, and a steady-state error of 0.02 %. In contrast, the TE-tuned controller (Kp = 1, Ki = 0.01, and Kd = 0.003) resulted in a rise time of 9 s, a delay time of 3 s, a settling time of 14 s, an overshoot of 0.03 %, and a steady-state error of 0.01 %. These results indicate that the ZN tuning produced a faster transient response but introduced a larger overshoot and a longer delay before reaching steady-state. The TE method, on the other hand, yielded a smoother and more stable performance characterized by lower overshoot, smaller steady-state error, and shorter delay. This behavior demonstrates the classical control trade-off between response speed and stability: ZN emphasizes rapid response through aggressive proportional–derivative action, whereas TE achieves better damping and robustness at the cost of slightly slower convergence.

Both methods maintained excellent steady-state accuracy (< 0.05 % error), confirming the effectiveness of PID control for the vibration system. For structural and soil–foundation experiments, where stability and precision are more critical than speed, the TE-tuned controller provides a more reliable configuration.

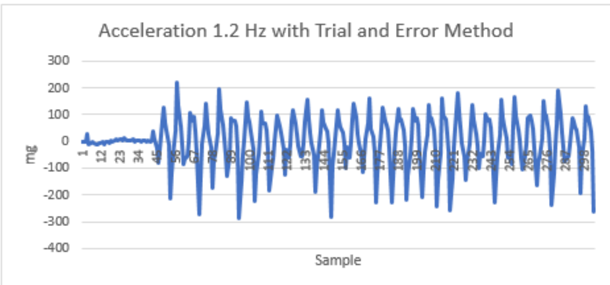

Fig. 11. Acceleration Graph Trial and Error Method

Fig. 9 and 11 show the acceleration responses obtained using the ZN and TE tuning methods, respectively. The acceleration signals correspond to the shaking table's motion measured by the accelerometer under 1.2 Hz excitation. The ZN response exhibits higher vibration amplitude and a more oscillatory transient phase, consistent with its aggressive control nature. In contrast, the TE response demonstrates smoother oscillations with lower amplitude, indicating better damping and reduced control effort. The difference between Fig. 8 and Fig. 10 also results from sensor placement. Fig. 9 represents acceleration recorded directly on the table surface, capturing actuator-induced vibration, whereas Fig. 11 shows acceleration transmitted through the foundation model and soil layer, where the signal experiences attenuation due to soil damping and energy dissipation. The noticeable reduction in amplitude in Fig. 11 confirms the damping effect of the soil medium, which absorbs and dissipates vibrational energy as it propagates from the table to the foundation. This attenuation behavior verifies that the system effectively simulates real soil–structure interaction, in which vibration energy decreases with depth because of frictional resistance, soil cohesion, and material damping. Comparison between the two tuning methods shows that the TE controller produces more stable acceleration patterns—an important factor in minimizing measurement noise during bearing-capacity evaluation.

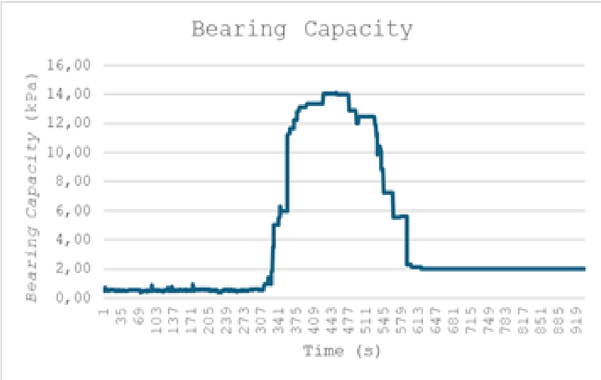

Fig. 12. Graph of Bearing Capacity

Fig. 12 presents the measured bearing capacity of the helical-pile foundation over time, obtained from the strain-gauge based load cell. The data show an initial stable region with negligible load, followed by a rapid increase in capacity reaching a peak of approximately 15 kPa, and finally a gradual decline and stabilization around a steady-state value of 3.99 kPa. Quantitative analysis produced the following performance indices, as shown in Table 2.

Table 2. Performance evaluation

Performance evaluation	Value
Mean Absolute Error (MAE)	5.00 kPa
Root Mean Square Error (RMSE)	6.01 kPa
Root Mean Square (RMS) of signal	8.37 kPa
Settling Time	≈ 900 s
Maximum Overshoot	≈ 281 %

The large overshoot indicates a strong dynamic-amplification effect caused by the combined inertia of the pile–soil system and the actuator's transient response. During the loading phase, the helical pile experienced progressive mobilization of shaft friction and end bearing, which resulted in the sharp increase in capacity. The subsequent decline and stabilization correspond to soil-strain softening and pore-pressure dissipation, leading to equilibrium at the effective bearing capacity of approximately 4 kPa. These trends are consistent with recent findings in dynamic foundation research. For example, Casablanca et al. (2023) developed a seismic bearing-capacity solution incorporating excess pore-pressures for shallow foundations under dynamic loads [13]. Alsanabani et al. (2024) investigated the influence of vertical vibration on bearing capacity of treated soils and confirmed that cyclic excitation can reduce effective bearing capacity over time [14]. Das (2025) reviewed axial capacities of helical piles and highlighted increased interest in dynamic loading behaviour of helical foundations [7]. The MAE and RMSE values confirm that the system exhibited moderate deviations during the transient state, while the RMS magnitude (8.37 kPa) shows that dynamic components dominate over purely static resistance. The long settling time (≈ 900 s) reflects the duration required for soil consolidation and stress redistribution following cyclic loading.

These findings demonstrate that the strain-gauge load cell effectively captured both static and dynamic load variations with high sensitivity. The helical-pile response reveals typical soil–structure interaction under vibration: an initial compaction and stiffening phase followed by gradual softening and stabilization [14], [7], [13]. The PID controller governs the shaking table's frequency and amplitude, which directly influences the vibration transmitted to the foundation. The Ziegler–Nichols (ZN) tuning generated higher acceleration amplitudes, which in turn caused greater transient loads and higher peak bearing capacity (dynamic amplification). Conversely, the Trial-and-Error (TE) tuning produced smoother excitation, yielding more stable and repeatable bearing-capacity measurements.

The observed correlation between acceleration and bearing capacity confirms that dynamic excitation intensity directly affects soil-resistance behaviour. This is supported by Alsanabani et al. (2024) and Casablanca et al. (2023), who found that cyclic and vibratory loads significantly influence mobilised capacity and failure mechanisms in foundations [14], [13]. Excessive oscillations increase transient stresses and may cause microstructural soil disturbance, potentially leading to over-estimation of short-term bearing capacity. Therefore, optimizing PID parameters becomes essential to ensure that the shaking table excitation replicates field conditions accurately without introducing measurement bias.

4. Conclusion

The results obtained from the shaking-table experiments highlight clear differences in the dynamic response of the system and the bearing-capacity performance of the helical-pile foundation. The helical pile achieved an average bearing capacity of 3.99 kPa, confirming its capability to sustain vertical loads under controlled vibration. This outcome reinforces the potential of helical piles as an effective foundation system for mitigating soil-liquefaction effects, enhancing structural safety, and minimizing damage during seismic or vibratory ground motions. A comparison between the Ziegler–Nichols (ZN) and Trial-and-Error (TE) PID tuning methods revealed distinct performance characteristics. The ZN method, with parameters Kp = 1, Ti=12, and Td=3, produced a rise time of 8 s, delay time of 13 s, settling time of 13 s, overshoot of 0.06 %, and steady-state error of 0.02 %.

Conversely, the TE method, with parameters Kp = 1, Ki = 0.01, and Kd = 0.003, yielded a rise time of 9 s, delay time of 3 s, settling time of 14 s, overshoot of 0.03 %, and steady-state error of 0.01 %. These findings demonstrate that the ZN tuning offers a faster transient response but introduces slightly higher overshoot and delay, whereas the TE tuning provides smoother and more stable control performance with lower overshoot and improved steady-state accuracy. Quantitative analysis of the helical-pile load data produced a Mean Absolute Error (MAE) of 5.00 kPa, Root Mean Square Error (RMSE) of 6.01 kPa, RMS value of 8.37 kPa, and a maximum overshoot of approximately 281 %, confirming the occurrence of strong dynamic amplification during vibration.

Overall, the integrated results confirm that the PID-controlled shaking table accurately replicates real-world vibration and soil–structure interaction. The Trial-and-Error tuning method is recommended for experiments requiring long-term stability and precise measurement of soil behavior, while the Ziegler–Nichols method is more suitable for studies emphasizing rapid dynamic excitation. The combined use of vibration control and helical-pile foundations offers a promising approach to enhancing the performance and resilience of civil structures subjected to seismic or dynamic loading conditions.

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References

[1] A. F. Hussein and B. H. El Naggar, “Seismic helical pile response in non-liquefiable and liquefiable soils,” J. Geotech. Geoenviron. Eng., vol. 148, no. 4, Art. no. 04021150, Apr. 2022.

[2] W. Fangfang, “Bearing performance of helical piles in sand under oblique tensile angle,” J. Central South Univ. (Sci. Technol.), vol. 52, no. 2, pp. 310–322, Feb. 2024.

[3] X. Yang, “Lateral dynamic response of helical pile in visco-elastic foundation,” Appl. Sci., vol. 13, no. 22, p. 12220, Nov. 2023.

[4] K. Jia, “Seismic behaviour of pile-supported pier-superstructure due to liquefaction lateral spreading,” Can. Geotech. J., vol. 61, no. 5, pp. 897-915, May 2024.

[5] M. Karim, D. Sakinah, D. N. Nuradryanto, S. Setiowati, R. N. Wardhani, A. Salimah, “Soil liquefaction measurement and adjustment system on shaking table for seismic simulation,” J. Eng. Appl. Technol., vol. 5, no. 1, pp. 52-64, Mar. 2024.

[6] A. Asgari et al., “Assessment of experimental data and analytical method of helical pile capacity under tension and compressive loading in dense sand,” Build. Eng., vol. 15, no. 15, p. 2683, 2025.

[7] D. Das, “Axial capacity of helical piles - A state of the art review,” Helical Piles & Deep Foundations, vol. 12, no. 1, pp. 15-29, 2025.

[8] W. Wu, “Theoretical analysis for dynamic response of helical pile pipe under dynamic loading,” Soil Dyn. Earthquake Eng., vol. 162, p. 108174, 2025.

[9] C. Vincent, “Comparison of static and dynamic load testing for pile bearing capacity,” Geomate J., vol. 30, no. 110, pp. 45-55, Jul. 2024.

[10] P. H. V. Nguyen, “Determining the load-bearing capacity of piles in Long An Province, Vietnam,” ETASR, vol. 21, no. 4, pp. 556-565, 2024.

[11] M. Esmailzade et al., “Experimental study on performance and enhanced bearing capacity of piles under dynamic loading,” Constr. Build. Mater., vol. 330, p. 127120, 2025.

[12] H. Cen et al., “Influence of P-wave oblique incidence on seismic subsidence of helical pile-soil model in marine soft soils,” Sci. Rep., vol. 15, p. 92808, 2025.

[13] O. Casablanca, “Bearing capacity of shallow foundations accounting for seismic excess pore pressures,” *Soil Dynamics & Earthquake Engineering*, vol. 173, p. 107417, 2023.

[14] N. Alsanabani, M. Al-Shamiri, and A. Alsanabani, “Influence of vertical vibration on the bearing capacity of cement-improved salt-encrusted soil,” *Alexandria Engineering Journal*, vol. 83, 2024.