MINISTRY OF EDUCATION AND TRAINING
MINISTRY OF AGRICULTURE AND ENVIRONMENT

VIET NAM ACADEMY FOR WATER RESOURCES
THE SOUTHERN INSTITUTE OF WATER RESOURCES RESEARCH

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RESEARCH ON THE AXIAL ULTIMATE BEARING CAPACITY OF SINGLE PILES RELATED TO THE INFLUENCE OF LIQUEFACTION POTENTIAL IN SANDY SOIL DUE TO EARTHQUAKE IN QUY NHON CITY

Specialization: GEOTECHNICAL ENGINEERING
Code: 9 58 02 11

SUMMARY OF THE DOCTORAL THESIS

HO CHI MINH CITY - 2025

The Thesis has been finished at

THE SOUTHERN INSTITUTE OF WATER RESOURCES RESEARCH

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At ……………..……on Date …… Month …….. Year 2025

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INTRODUCTION

1. The urgency of the research topic

Liquefaction of soil is a combination of wave phenomenon with saturation of soil consolidation caused by earthquakes that damages the foundation structure of high-rise buildings. In recent years, aftershocks caused by earthquakes have appeared more frequently in Vietnam in general and in the Central provinces of Vietnam in particular, in which, Quy Nhon city, Gia Lai province, in the Central region, is located in the earthquake zone of level 6.5 ÷ 7.0, where the density of high-rise buildings and bridges and roads is increasing, reflected in the quantity, quality, scale and importance of the works. Currently, the pile foundation system of high-rise buildings in Quy Nhon city, Gia Lai province is lowered through layers of sandy soil without related to the influence of liquefaction potential in sandy soil due to earthquake.

For that reason, the study of changes in some durability parameters of sandy soil in Quy Nhon city, Gia Lai province according to the compressive-tensile stress paths under repeated loading by cyclic triaxial test to find dynamic durability parameters to evaluate the decrease in the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential in sandy soil due to earthquake is an urgent need and practical significance. From the above analysis, the main objective of the thesis is to study the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential in sandy soil due to earthquake, which is a necessary issue with scientific significance, contributing to a more comprehensive consideration of the method of calculating pile foundations of works in Vietnam.

2. Objectives of research

- Determination of mechanical properties of sandy soil when subjected to dynamic loading, including cyclic shear stress ratio and excess pore water pressure ratio, rules for the change in cyclic shear stress ratio, excess pore water pressure ratio with the number of cycle n according to the stress paths (CTC, CTC-RTE, RTE) corresponding to frequency 1 Hz and frequency 2 Hz.
- The study proposed some appropriate dynamic stability parameters (cyclic shear stress ratio and excess pore water pressure ratio) by cyclic triaxial test corresponding to frequency 1 Hz and frequency 2 Hz to calculate the ultimate

bearing capacity of single piles related to the influence of liquefaction potential in sandy soil due to earthquake in Quy Nhon city, Gia Lai province.

3. Research content of the thesis

- Overall study on the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential in sandy soil due to earthquake.
- Research on the theoretical basis of some dynamic stability parameters (cyclic shear stress ratio, excess pore water pressure ratio) in sandy soil related to the influence of liquefaction potential due to earthquake.
- From the results obtained on the cyclic shear stress ratio, the excess pore water pressure ratio by cyclic triaxial test according to the stress paths (CTC, CTC-RTE, RTE) corresponding to the frequency of 1 Hz and the frequency of 2 Hz for the sandy soil in the Quy Nhon city, Gia Lai province. From there, the cyclic shear stress ratio and the excess pore water pressure ratio corresponding to the frequency of 1 Hz and the frequency of 2 Hz and the number of cycles n were established.
- Apply to calculate the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential in sandy soil due to earthquake for calculating actual works according to the results of the cyclic triaxial test, theoretical formula and numerical simulation by Geostudio 2018 software.

4. Objects and scope of research

- Objects of research: Determining the excess pore water pressure ratio of sandy soil in medium compact state, to calculate the design of the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential in sandy soil due to earthquake for civil works in Quy Nhon city, Gia Lai province.
- Scope of research: *(1).* This is a study on loose sandy soil with medium compact state, commonly distributed in Quy Nhon city, Gia Lai province at depths from 0 m to 10 m by cyclic triaxial test. *(2).* The thesis focuses on studying dynamic durability characteristics such as excess pore water pressure ratio and cyclic shear stress ratio of sandy soil by cyclic triaxial tests corresponding to frequency f = 1 Hz and frequency f = 2 Hz, these ratios have a great influence on the axial ultimate bearing capacity of single piles related to liquefaction potential in sandy soil due to earthquake to design civil works in Quy Nhon city, Gia Lai province.

5. Research methods

- Statistical methods: To collect and analyze documents base on the results of theoretical and experimental research on calculations for the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential in sandy soil due to earthquake to design civil works in domestic and international. To statistic and analyze of soil test results, regional geological characteristics, calculation of the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential in sandy soil due to earthquake for two projects in Quy Nhon city, Gia Lai province.
- Experimental method: To survey and take field samples using standard penetration test (SPT), static pile load testing, dynamic pile load testing (Pile Driving Analyzer - PDA). To perform experiments in the laboratory using cyclic triaxial test - Tritech 100.
- Numerical simulation method: To use the finite element method by Geostudio 2018 software to simulate the soil and piles to determine the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential in sandy soil due to earthquakes. From there, compare the results between calculations by Geostudio 2018 software and theoretical calculations for two projects.

6. The new contributions of the thesis

- Finding out durability parameters of sandy soil in Quy Nhon city, Gia Lai province, considering the liquefaction phenomenon of sandy soil by cyclic triaxial test.
- Suggestion for correlation between cyclic shear stress ratio (CSR) and excess pore water pressure ratio (r_u).
- Proposed a formular to calculate the axial ultimate bearing capacity of single piles with some improvements (using excess pore water pressure ratio, r_u) for sandy soil in the Quy Nhon city, Gia Lai province related to the influence of liquefaction potential in sandy soil due to earthquake.

7. Scientific and practical significance of the thesis

- The research results of this thesis contribute to the methodology of sandy soil in the study area, initially clarifying the law of changes in the physical and mechanical characteristics of popular sandy soil in the Quy Nhon city, Gia Lai province by the stress paths (CTC, CTC-RTE, RTE) which are used to design the axila ultimate bearing capacity of single piles related to the influence of liquefaction potential in sandy soil due to earthquake.

- The research results provide a scientific basis and argument to guide the survey and design of the axila ultimate bearing capacity of single piles related to liquefaction potential in sandy soil due to earthquake in Quy Nhon city, Gia Lai province. The research results of this thesis can also be used as reference in the design of the axial ultimate bearing capacity of single piles related to the liquefaction potential in sandy soil due to earthquakes for other areas have the similar ground conditions.

8. Structure of the Thesis

Declaration - Thanking.

Table of tables, figures, notation.

The thesis structure includes the following contents:

Introduction

Chapter 1. Overview of the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential in sandy soil due to earthquake

Chapter 2. Theoretical basis of the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential in sandy soil due to earthquake

Chapter 3. Research on cyclic shear stress ratio, excess pore water pressure ratio by cyclic triaxial test according to stress paths

Chapter 4. The axial ultimate bearing capacity of single piles related to the influence of liquefaction potential in sandy soil due to earthquake for actual work in Quy Nhon city

Conclusions and Recommendations

References

Publication

Appendix

CHAPTER 1.
OVERVIEW OF THE AXIL ULTIMATE BEARING CAPACITY OF SINGLE PILES RELATED TO THE INFLUENCE OF LIQUEFATION POTENTIAL IN SANDY SOIL DUE TO EARTHQUAKE

1.1. Overview of the phenomenon of liquefaction for sandy soil due to earthquake

1.2. Research situation abroad

1.3. Research situation in the country

1.4. Research on the characteristics of sandy soil in the central region

1.4.1. Overview of geological characteristics in the central region

1.4.2. Topographic and geological characteristics of the area in Quy Nhon city, Gia Lai province

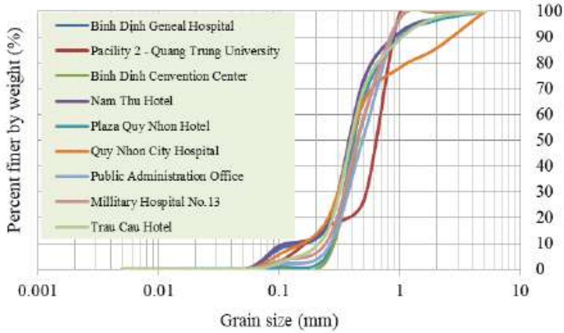


Figure 1.1. *Grain size distribution curve of typical geology coastal area of Quy Nhon city, Gia Lai province*

1.5. Conclusion for Chapter 1

- The grain size distribution curve for the sandy soil in the research area in Quy Nhon city, Gia Lai province is located within the boundary of the liquefaction sandy soil curve of Tsuchida (1970). This is the basis for preliminary assessment of the sandy soil in the research area related to the influence of liquefaction potential in sandy soil due to earthquake in Quy Nhon City, Gia Lai province.

- The consideration of the correlation of sandy soil considering the liquefaction potential as the displacement state of sandy soil to evaluate the shear strain γ (%) of the soil according to the change of the standard penetration test index (N_{60}), the value of shear strain γ (%) increases, the value of the standard penetration test index (N_{60}) decreases according to Boulanger et al. (2006), using the shaft resistance coefficient β when calculating the shaft resistance of the pile and the tip resistance coefficient (N_t) of pile when calculating the tip resistance of pile according to Fellenius and Siegel (2008), based on the results of the standard penetration test (N_{spt}) and direct shear test in the laboratory (c, φ, γ_w, ...) according to Muhunthan et al. (2017), ... so there are still many limitations.

From the above overview, the tasks set for the thesis are as follows:

- Research on establishing the ground acceleration band according to time corresponding to frequency f = 1 Hz and frequency f = 2 Hz.
- From the results of field experiments, laboratory experiments and cyclic triaxial tests, the correlation between CSR and r_u and the number of cycles n were established, the correlation between CSR and r_u and the standard penetration test index (N_{60}), internal friction angle (φ) and internal friction angle with liquefaction potential (φ') and the number of cycles n corresponding to the frequency of 1 Hz and the frequency of 2 Hz were established.
- Determine the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential in sandy soil due to earthquake according to theoretical formulas and numerical methods by Geostudio 2018 software corresponding to frequencies f = 1 Hz and f = 2 Hz.
- Propose and re-check the excess pore water pressure ratio (r_u) according to the standard penetration index (N_{60}) corresponding to the frequency f = 1 Hz and the frequency f = 2 Hz to calculate the axial ultimate bearing capacity of pile related to influence of liquefaction potential in sandy soil due to earthquake for the area in Quy Nhon City, Gia Lai province.

CHAPTER 2.
THEORETICAL BASIS OF THE AXIL ULTIMATE BEARING CAPACITY OF SINGLE PILES RELATED TO THE INFLUENCE OF LIQUEFATION POTENTIAL IN SANDY SOIL DUE TO EARTHQUAKE

2.1. General introduction

2.2. Construction of the ground acceleration range due to earthquakes from the harmonic response spectrum

2.3. Soil models in Geostudio 2018 software

2.4. Calculation application for geology of the research area

2.5. Determining the liquefaction resistance coefficient of sandy soil from standard penetration test results

2.6. Research on methods for determining the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential in sandy soil

2.6.1. The axial ultimate bearing capacity of single piles related to the influence of liquefaction potential in sandy soil according to Boulanger et al.

2.6.2. The axial ultimate bearing capacity of single piles related to the influence of liquefaction potential in sandy soil according to Fellenius et al. (2008)

2.6.3. The axial ultimate bearing capacity of single piles related to the influence of liquefaction potential in sandy soil according to Muhunthan et al. (2017)

2.6.4. The axial ultimate bearing capacity of single piles related to the influence of liquefaction potential in sandy soil (proposed)

2.7. Reliability index β_T

2.8. Conclusion of chapter 2

- Construction of an earthquake-resistant ground acceleration band from the theoretical harmonic response spectrum and a harmonic acceleration band by Geostudio software for sandy soils of typical geological areas in Quy Nhon city, Gia Lai province corresponds to frequency f = 1 Hz and frequency f = 2 Hz.
- Methods for calculating the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential in sandy soil such as Boulanger et al. (2004) method, Fellenius et al. (2008) method, Muhunthan et al. (2017) method, ... still have many limitations, because it is necessary to multiply by coefficients with quite large values, these methods also consider the decrease in the average shaft resistance strength of the pile, however, these methods have not yet mentioned the decrease in the shaft pile resistance due to changes in void ratio (e_v) or changes in the value of the excess pore water pressure ratio (r_u).
- Studying the changes in dynamic strength parameters such as excess pore water pressure ratio (r_u), cyclic shear stress ratio (CSR), ... for stress paths when compressing (CTC), when tensile (RTE) or both compressing and tensile (CTC-RTE) over time or cycles by cyclic triaxial test for sandy soil samples to establish some correlations in dynamic strength parameters (CSR, r_u, ...) corresponding to frequency f = 1 Hz and frequency f = 2 Hz, serving the calculation of the axial ultimate bearing capacity of single piles related to the

influence of liquefaction potential for typical sandy soil in Quy Nhon city, Gia Lai province will be the main content presented in Chapter 3.

CHAPTER 3.
RESEARCH ON CYCLIC SHEAR STRESS RATIO, EXCESS PORE WATER PRESSURE RATIO BY CYCLIC TRIAXIAL TEST ACCORDING TO STRESS PATHS

3.1. Purpose, theoretical basis and equipment of the cyclic triaxial test

3.1.1. Purpose of the cyclic triaxial test

3.1.2. Stress Path in the cyclic triaxial test

Stress paths such as: CTC; CTC-RTE and RTE

3.1.3. Stress conditions of the cyclic triaxial test for saturated sandy soil samples

3.1.4. Determination of the stress amplitude range for the cyclic triaxial test

3.1.5. Natural oscillation frequency for the studied sandy soil

3.1.6. Cyclic shear stress ratio CSR'

3.1.7. Equipment for the cyclic triaxial test

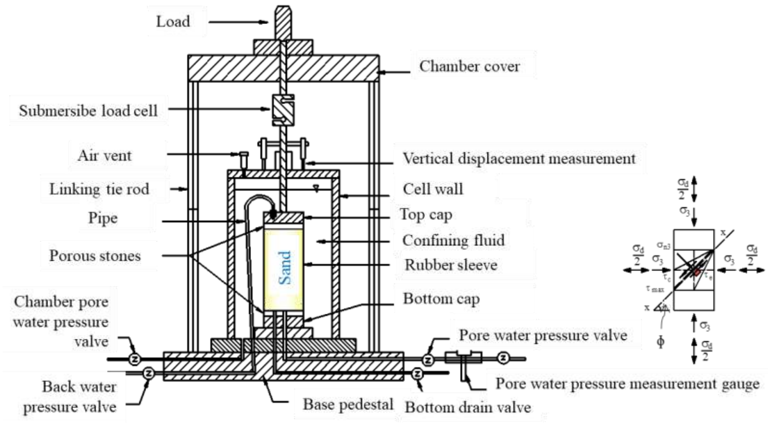


Figure 3.1. *Schematic diagram of the equipment for the cyclic triaxial test - Tritech 100*

3.2. Perform experiments

3.2.1. Experimental testing according to stress paths (CTC, CTC-RTE, RTE)

3.2.2. Geological and mechanical characteristics of the reasche area

3.2.3. Test specimen

3.2.4. Parameters for undrained cyclic triaxial test

3.2.5. Test data processing

3.3. Test results

Table 3.1. *Results of undrained cyclic triaxial test*

Depth	Sand sample	D_r (After consolidation)	f (Hz)	Vibration mode	Vibration amplitude (kPa)	CSR'	Deformation amplitude (%)	r_u (max)	State
1-2m	C1	0.101	1	CTC	7.5	0.286	3.27	100.00	Liq
1-2m	C2	0.343	1	CTC	10	0.150	0.22	3.30	No
1-2m	C3	0.385	1	CTC-RTE	14	0.212	0.11	4.85	No
1-2m	C3-1	0.363	1	CTC-RTE	18	0.274	0.17	10.03	No
1-2m	C3-3	0.488	2	CTC-RTE	30	0.455	0.28	10.91	No
1-2m	C5	0.298	2	RTE	20	0.556	4.44	70.00	Destroy
2-4m	CC1	0.172	2	CTC-RTE	12.5	0.164	1.58	100.00	Liq
2-4m	CC1-1	0.174	1	CTC-RTE	12.5	0.165	3.62	100.00	Liq
2-4m	CC2	0.373	2	CTC-RTE	25	0.391	4.15	100.00	Liq
2-4m	CC2-2	0.357	1	CTC-RTE	25	0.380	5.84	99.09	Liq
2-4m	CC3	0.316	2	RTE	7.5	0.341	1.97	100.00	Liq
2-4m	CC3-3	0.255	1	RTE	7.5	0.338	4.37	100.00	Liq
2-4m	CC4	0.298	2	CTC-RTE	15	0.417	1.80	100.00	Liq
2-4m	CC4-4	0.251	1	CTC-RTE	15	0.444	3.25	100.00	Liq
4-6m	CS1	0.226	1	CTC-RTE	8	0.308	0.08	16.92	No
4-6m	CS2	0.218	1	CTC-RTE	15	0.577	2.42	100.00	Liq
4-6m	CS2-1	0.216	2	CTC-RTE	15	0.536	2.07	100.00	Liq
4-6m	CS3	0.251	1	CTC-RTE	8	0.250	1.97	83.75	Destroy
4-6m	CS5	0.353	5	CTC-RTE	14	0.206	0.09	5.29	No
4-6m	CS7	0.178	2	CTC-RTE	30	0.441	0.14	27.06	No

3.3.1. Relationship between sand parameters and number of cycles n for liquefied sand samples

3.3.2. Correlation between CSR_{gh}, r_u and number of cycles n for liquefied sand samples

3.3.3. Stress envelope CSR_{gh} and number of cycles n

3.3.4. Correlation between r_u and number of cycles n

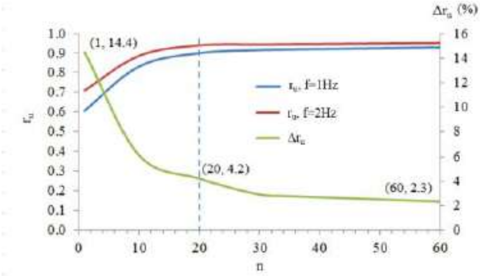


Figure 3.2. *Relationship between r_u, Δr_u and n*

3.3.5. Correlation between r_u and CSR and different frequencies (Figure 3.3)

3.3.6. Correlation between k, r_u and the number of cycle n (Figure 3.4)

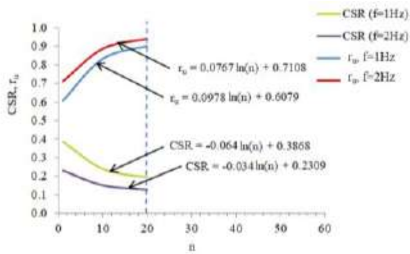


Figure 3.3. *Relationship between CSR, r_u and n*

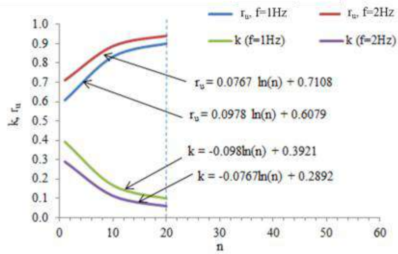


Figure 3.4. *Relationship between k, r_u and n*

3.4. Conclusion of chapter 3

- Establish the envelope for the cyclic shear stress ratio (CSR_{gh}) according to the number of cycle n corresponding to the frequency f = 1 Hz and the frequency f = 2 Hz.
- The cyclic shear stress ratio (CSR) decreases corresponding to the increase in the number of cycle n (n = 1 cycle to n = 20 cycle), establishing the correlation between CSR and the number of cycle n as follows:

$CSR = -0.064\ln(n) + 0.3868$ for frequency f = 1 Hz, $CSR = -0.034\ln(n) + 0.2309$ for frequency f = 2 Hz.

- The excess pore water pressure ratio (r_u) increases corresponding to the number of cycle n increasing (n = 1 cycle to n = 20 cycle), establishing the correlation between r_u and n: $r_u = 0.0978\ln(n) + 0.6079$ for frequency f = 1 Hz, $r_u = 0.0767\ln(n) + 0.7108$ for frequency f = 2 Hz. Specifically, when n = 1 cycle, the value of r_u = 0.60 corresponding to a frequency of 1 Hz and the value of r_u = 0.71 corresponding to a frequency of 2 Hz. When n = 20 cycles, the value of r_u = 0.90 corresponding to a frequency of 1 Hz and the value of r_u = 0.94 corresponding to frequency of 2 Hz.
- With the number of cycle n from 1 cycle to 20 cycle, the relationship between the r_u ratio and the CSR ratio is nonlinear, the value of the CSR ratio decreases and the value of the r_u ratio increases corresponding to different frequencies, establishing a correlation between r_u ratio and CSR ratio: $r_u = -0.8660CSR + 0.8702$ corresponding to the frequency f = 1 Hz, $r_u = -2.255CSR + 1.2316$ corresponding to frequency f = 2 Hz.
- With the number of cycle n from 1 cycle to 20 cycle, the value of the degradation resistance factor (k) is smaller while the number of cycle n is larger corresponding to frequency f = 1 Hz and frequency f = 2 Hz, here k is tgφ'/tgφ, with $k = -0.098\ln(n) + 0.3921$ corresponding to frequency f = 1 Hz and $k = -0.0767\ln(n) + 0.2892$ corresponding to requency f = 2 Hz.

Based on this result, it is possible to add a prediction of the internal friction angle due to the decrease when related to the influence of liquefaction potential (φ') and compare it with TCVN 10304:2014.

CHAPTER 4.
THE AXIAL ULTIMATE BERING CAPACITY OF SINGLE PILES RELATED TO THE INFLUENCE OF LIQUEFACTION POTENTIAL IN SANDY SOIL DUE TO EARTHQUAKE FOR ACTUAL WORK IN QUY NHON CITY

4.1. Contents of calculating the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential

- Calculation of the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential for typical sandy soil according to by Boulanger et al. (2004) method, Fellenius et al. (2008) method, Muhunthan et al. (2017) method, PP4, Geostudio 2018 software and Vietnam construction standards (TCVN 10304:2014 standard) for 02 projects in Quy Nhon city, Gia Lai province (Nam Thu Hotel project and General Hospital project).
- Using the data set from the results of the cyclic triaxial test corresponding to frequency f = 1 Hz and frequency f = 2 Hz to simulate the calculation of the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential for sandy soil by Geostudio 2018 software.

4.2. Calculation application for the Nam Thu Hotel project

4.2.1. Introduction

4.2.2. Construction geology

4.2.3 Results of dynamic pile load testing (PDA test)

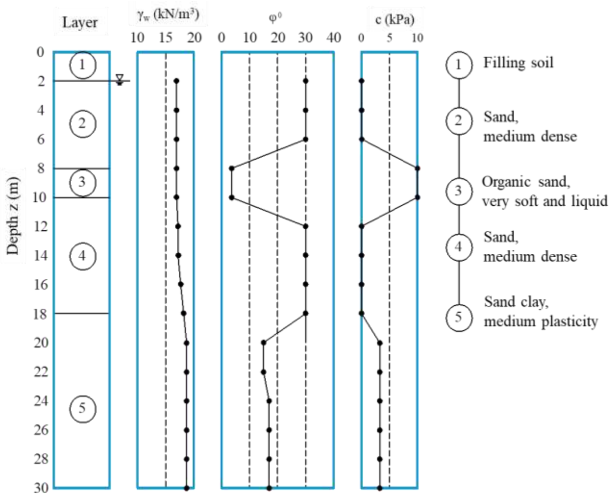


Figure 4.1. *Geological conditions of the Nam Thu Hotel project*

Conducting dynamic pile load testing (PDA) according to ASTM D4945 standard for pile No. CTN2-T7 of 10-storey building, CTN2-T7 pile is a reinforced concrete pile with diameter D600, Mac 300, with CTN2-T7 pile having pile length l_p = 24 m, tip of pile at depth in clay soil layer. The design load of pile Q_a = 1400 (kN), axila ultimate bearing capacity of single pile

$Q_{d,PDA}$ = 2650 kN, pile shaft resistance $R_{TN,s}$ = 1920 kN, pile tip resistance $R_{TN,t}$ = 730 kN, groundwater level is from 2.0 m to 3.0 m deep.

4.2.4. Simulation and results by Geostudio 2018 software

4.2.4.1. Choose a suitable background model

Table 4.1. *Physical and mechanical parameters and pile of Nam Thu Hotel project*

Parameter	Symbol	Unit	Filling soil	Layer 2 Sand, medium dense	Layer 3 Organic sand, very soft and liquid	Layer 4 Sand, medium dense	Layer 5 Sand clay, medium plasticity	Pile
Material model	Model	-	Linear Elastic	Equivalent Linear	Linear Elastic	Equivalent Linear	Linear Elastic	Linear Elastic
Material behavior	Type	-	Drained	Drained	Drained	Drained	Drained	Non - porous
Depth	z	m	0 ÷ 2	2 ÷ 8	8 ÷ 10	10 ÷ 18	18 ÷ 30	-
Unit weight	γ_w	kN/m^3	17.2	17.3	17.2	17.6	19.6	24
Interface friction angle	φ	degree (^{0})	32.94	30	4	30	14.5	
Cohesion	c	kPa	-	0	10	0	19	
Poisson ratio	ν	-	0.2	0.3	0.35	0.3	0.35	0.1
Damping ratio	ξ	-	0.2	0.24	0.25	0.23	0.22	
Model factor	α	-	0.7	0.72	0.7	0.72	0.7	
Maximum shear modulus	G_{max}	kPa	10000	50000	11000	55000	27400	

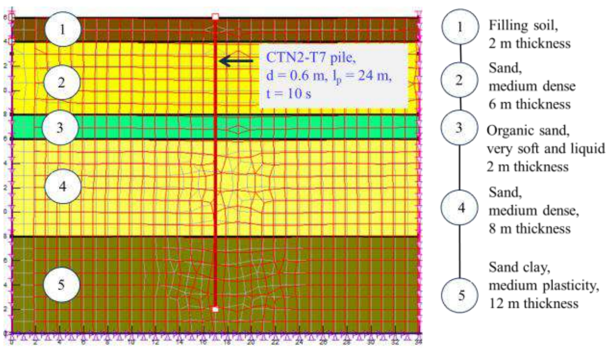


Figure 4.2. *Numerical simulation of the project after completion of pile construction*

4.2.4.2. Applying results using calculation software

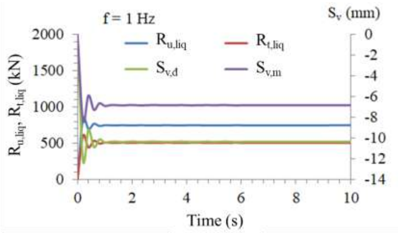


Figure 4.3. *Relationship between $R_{u,liq}$, $R_{t,liq}$ and S_v of pile with time for frequency f = 1 Hz*

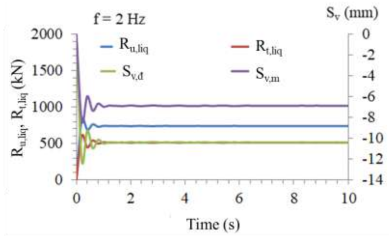


Figure 4.4. *Relationship between $R_{u,liq}$, $R_{t,liq}$ and S_v of pile with time for frequency f = 2 Hz*

Conclusion of results by Geostudio 2018 software

- Using the linear elastic model (LE), equivalent linear model (EL) in the simulation by Geostudio software to calculate the above problem. The result of the equivalent linear model (EL) is choose.

- As a result, the axial ultimate bearing capacity of pile related to the influence of liquefaction potential ($R_{u,liq}$) simulated due to earthquake according to the EL model is 714.1 kN and tip resistance of pile related to influence of liquefaction potential ($R_{t,liq}$) simulated due to earthquake according to the EL model is 506.4 kN corresponding to frequency f = 1 Hz, the ultimate bearing capacity of pile related to influence of liquefaction potential ($R_{u,liq}$) simulated due to earthquake according to the EL model is 706.7 kN and tip resistance of pile related to influence of liquefaction potential ($R_{t,liq}$) simulated due to earthquake according to the EL model is 510.5 kN corresponding to frequency f = 2 Hz. The degradation difference is 41.70 % for $R_{u,liq}$ of pile and 30.64 % for $R_{t,liq}$ of pile corresponding to frequency f = 1 Hz, similarly, the degradation difference is 42.23 % for $R_{u,liq}$ of pile and 30.07 % for $R_{t,liq}$ corresponding to frequency f = 2 Hz.

4.2.5. Establishing correlations and evaluating results for bored pile

4.2.5.1. Evaluation of liquefaction resistance factor (FS_{liq}) and depth z

4.2.5.2. Cyclic shear stress ratio (CSR) and N_{60}

4.2.5.3. Excess pore water pressure ratio (r_u) versus N_{60}

4.2.5.4. Axial ultimate bearing capacity ($Q_{u,liq}$) of pile according to methods

Table 4.2. *Axial ultimate bearing capacity of pile and resistance coefficients of pile according to methods*

Method	Shaft resistance		Tip resistance		Axial ultimate bearing capacity	
	$R_{s,liq}$ (kN)	k_s	$R_{t,liq}$ (kN)	k_t	$R_{u,liq}$ (kN)	k_u
Boulanger et al. (2004)	115.8	0.06	483.3	0.66	599.1	0.23
Fellenius et al. (2008)	110.0	0.06	663.1	0.91	773.1	0.29
Muhunthan et al. (2017)	67.4	0.04	486.3	0.67	553.7	0.21
PP4, f = 1 Hz	45.5	0.03	634.1	0.87	679.6	0.26
PP4, f = 2 Hz	36.4	0.02	634.1	0.87	670.5	0.25
Geostudio 2018, f = 1 Hz	207.7	0.11	506.4	0.69	714.1	0.28
Geostudio 2018, f = 2 Hz	196.2	0.10	510.5	0.70	706.7	0.28
PDA	1921.0	1.00	729.0	1.00	2650.0	1.00
TCVN 10304:2014	151.0	0.08	634.1	0.87	785.1	0.30

Table 4.3. *Axial ultimate bearing capacity of piles and degradation level of pile*

Method	Shaft resistance		Axial ultimate bearing capacity	
	$R_{s,liq}$ (kN)	$\Delta R_{s,liq,4\text{-}5}$ (%)	$R_{u,liq}$ (kN)	$\Delta R_{u,liq,4\text{-}5}$ (%)
PP4, f = 1 Hz	45.5	69.80	679.6	13.40
PP4, f = 2 Hz	36.5	75.70	670.6	14.60
TCVN 10304:2014	151.0	-	785.1	-

4.2.5.5. Axial ultimate bearing capacity ($Q_{u,liq}$) of pile over time

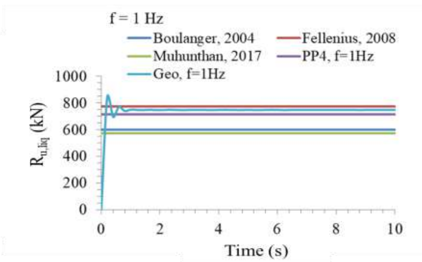
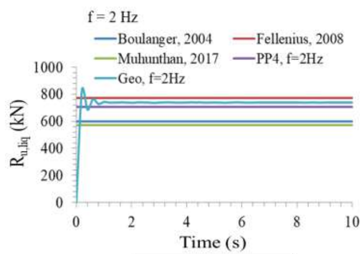


Figure 4.5. *Relationship between axial ultimate bearing capacity of pile and time for frequency f = 1 Hz*



Hình 4.6. *Relationship between axial ultimate bearing capacity of pile and time for frequency f = 2 Hz*

4.2.5.6. Evaluation of reliability index β_T

According to the proposed method (PP4), the value of β_T = 2.533 corresponding to the frequency f = 1 Hz is smaller than the value of β_T = 2.535 corresponding to the frequency f = 2 Hz.

4.3. Calculation application for General Hospital project in Binh Dinh province

4.3.1. Introduction

4.3.2. Construction geology

4.3.3. Experimental results of static load testing of piles using the drilling and pressing method

Conducting axial compressive load testing (ACL) of pile according to TCVN 269:2002 standard at the General Hospital Project (Binh Dinh Province), item 9-storey Treatment Building. The technical specifications of reinforced concrete square piles are 400 mm side, Mac 300 with E_p = 28.5.106 kN/m^2, pile length l_p = 16 m, borehole diameter 350 mm for the 84a pile, and tip of pile at depth in sandy soil layer. The time of axial compressive load testing of pile is from 28/02/2011 to 03/03/ 2011 (05 days). The design load of pile Q_a = 800 (kN), axial compressive load testing of pile $Q_{d,NT}$ = 2000 kN, pile shaft resistance $R_{s,NT}$ = 1002 kN, pile tip resistance $R_{t,NT}$ = 998 kN and safety resistance factor of pile is 2.5.

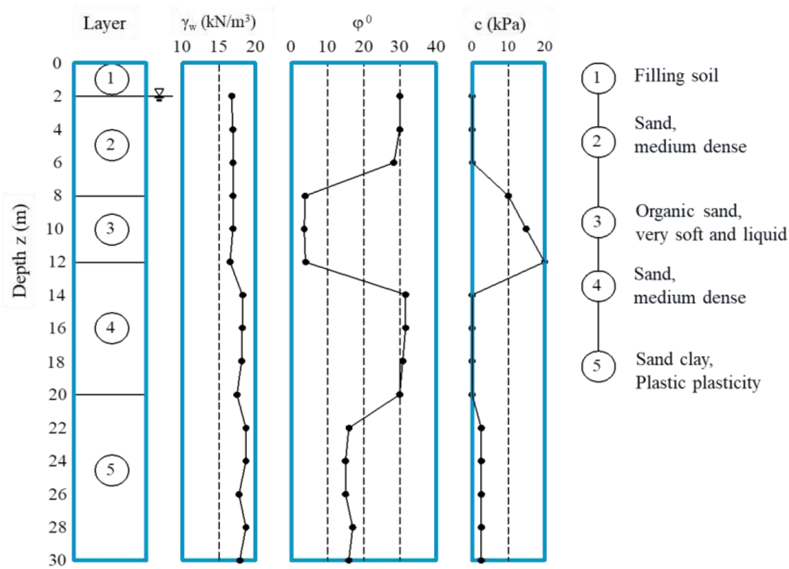
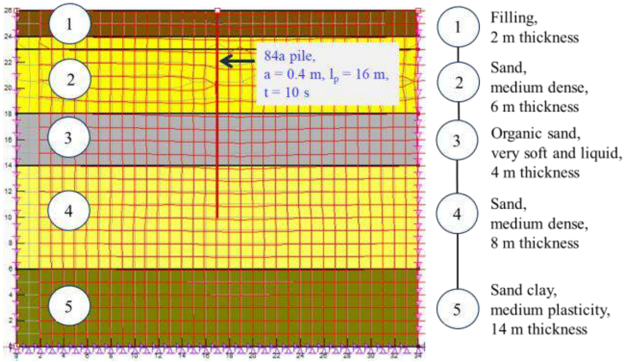


Figure 4.7. *Geological conditions of the General Hospital project*

4.3.4. Simulation and results by Geostudio 2018 software

4.3.4.1. Choose a suitable background model

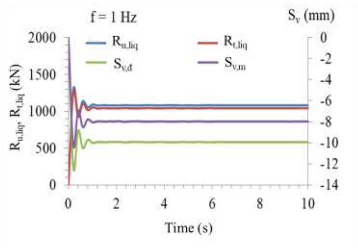


Hình 4.8. *Numerical simulation of the project after completion of pile construction*

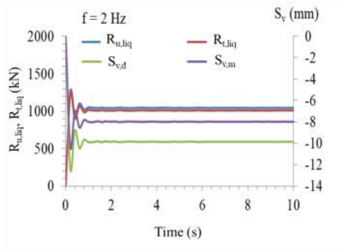
Table 4.4. *Physical and mechanical parameters and pile of General Hospital project*

Parameter	Symbol	Unit	Filling soil	Layer 2 Sand, medium dense	Layer 3 Organic sand, very soft and liquid	Layer 4 Sand, medium dense	Layer 5 Sand clay, plastic plasticity	Pile
Material model	Model	-	Linear Elastic	Equivalent Linear	Linear Elastic	Equivalent Linear	Linear Elastic	Linear Elastic
Material behavior	Type	-	Drained	Drained	Drained	Drained	Drained	Non - porous
Depth	z	m	0 ÷ 2	2 ÷ 8	8 ÷ 12	12 ÷ 20	20 ÷ 30	-
Unit weight	γ_w	kN/m^3	17.2	17.4	16.8	17.3	18.6	24
Interface friction angle	φ	degree (^{0})	32.94	30	5.4	32	17.4	
Cohesion	c	kPa	-	0	12	0	5	
Poisson ratio	ν	-	0.2	0.3	0.35	0.3	0.35	0.1
Damping ratio	ξ	-	0.2	0.24	0.25	0.23	0.22	
Model factor	α	-	0.7	0.72	0.7	0.72	0.7	
Maximum shear modulus	G_{max}	kPa	-	50000	11000	55000	27400	

4.3.4.2. Applying results using calculation software



Hình 4.9 . *Relationship between $R_{u,liq}$, $R_{t,liq}$ and S_v of pile with time for frequency f = 1 Hz*



Hình 4.10. *Relationship between $R_{u,liq}$, $R_{t,liq}$ and S_v of pile with time for frequency f = 2 Hz*

Conclusion of results by Geostudio 2018 software

- Using the linear elastic model (LE), equivalent linear model (EL) in the simulation by Geostudio software to calculate the above problem. The result of the equivalent linear model (EL) is choose.
- As a result, the axial ultimate bearing capacity of pile related to the influence of liquefaction potential ($R_{u,liq}$) simulated due to earthquake according to the EL model is 947.42 kN and tip resistance of pile related to influence of liquefaction potential ($R_{t,liq}$) simulated due to earthquake according to the EL model is 834.43 kN corresponding to frequency f = 1 Hz, the ultimate bearing capacity of pile related to influence of liquefaction potential ($R_{u,liq}$) simulated due to earthquake according to the EL model is 898.14 kN and tip resistance of pile related to influence of liquefaction potential ($R_{t,liq}$) simulated due to earthquake according to the EL model is 809.28 kN corresponding to frequency f = 2 Hz. The degradation difference is 52.63 % for $R_{u,liq}$ of pile and 16.39 % for $R_{t,liq}$ of pile corresponding to frequency f = 1 Hz, similarly, the degradation difference is 55.09 % for $R_{u,liq}$ of pile and 18.91 % for $R_{t,liq}$ corresponding to frequency f = 2 Hz.

4.3.5. Establishing correlations and evaluating results for pile

4.3.5.1. Evaluation of liquefaction resistance factor (FS_{liq}) and depth z

4.3.5.2. Cyclic shear stress ratio (CSR) and N_{60}

4.3.5.3. Excess pore water pressure ratio (r_u) versus N_{60}

4.3.5.4. Axial ultimate bearing capacity ($Q_{u,liq}$) of pile according to methods

Table 4.5. *Axial ultimate bearing capacity of pile and resistance coefficients of pile according to methods*

Method	Shaft resistance		Tip resistance		Axial ultimate bearing capacity	
	$R_{s,liq}$ (kN)	k_s	$R_{t,liq}$ (kN)	k_t	$R_{u,liq}$ (kN)	k_u
Boulanger et al. (2004)	50.9	0.05	1379.9	1.38	1430.8	0.72
Fellenius et al. (2008)	57.9	0.06	1862.8	1.87	1920.7	0.96
Muhunthan et al. (2017)	38.7	0.04	1838.4	1.84	1877.1	0.94
PP4, f= 1 Hz	24.4	0.02	1028.1	1.03	1052.5	0.53
PP4, f= 2 Hz	11.6	0.01	1028.1	1.03	1039.7	0.52
Geostudio 2018, f= 1 Hz	113.0	0.11	834.4	0.84	947.4	0.47
Geostudio 2018, f= 2 Hz	88.9	0.09	809.3	0.81	898.1	0.45
ACL testing	1002.0	1.00	998.0	1.00	2000.0	1.00
TCVN 10304:2014	55.8	0.06	1028.1	1.03	1083.9	0.54

Table 4.6. *Axial ultimate bearing capacity of piles and degradation level of pile*

Method	Shaft resistance		Axial ultimate bearing capacity	
	$R_{s,liq}$ (kN)	$\Delta R_{s,liq,4\text{-}5}$ (%)	$R_{u,liq}$ (kN)	$\Delta R_{u,liq,4\text{-}5}$ (%)
PP4, f= 1 Hz	24.4	56.27	1054.8	2.68
PP4, f= 2 Hz	11.6	79.21	1039.7	4.07
TCVN 10304:2014	55.8	-	1083.9	-

4.3.5.5. Axial ultimate bearing capacity ($Q_{u,liq}$) of pile over time

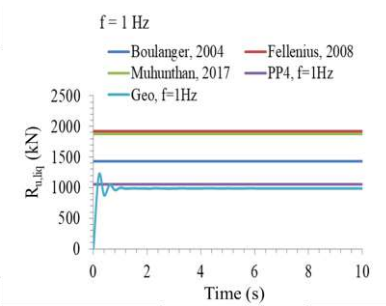


Figure 4.11. *Relationship between axial ultimate bearing capacity of pile and time for frequency f = 1 Hz*

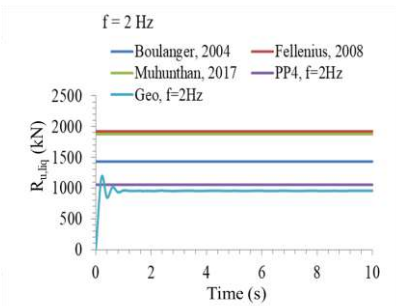


Figure 4.12. *Relationship between axial ultimate bearing capacity of pile and time for frequency f = 2 Hz*

4.3.5.6. Evaluation of reliability index β_T

According to the proposed method (PP4), the value of β_T = 1.704 corresponding to the frequency f = 1 Hz is smaller than the value of β_T = 1.707 corresponding to the frequency f = 2 Hz.

4.4. Comments on chapter 4

- The cyclic shear stress ratio (CSR) increases and the pore water pressure ratio (r_u) decreases nonlinearly with the increase of the standard penetration test (N_{60}) for medium-grained sand, corresponding to medium density.

- From the analysis results, the calculation of the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential for typical sandy soil according to the methods by Boulanger et al. (2004), Fellenius et al. (2008), Munhunthan et al. (2017), Geostudio 2018 software and the author's proposed method are similar, but there is a difference compared to the calculation method according to and Vietnam construction standards (TCVN 10304:2014 standard).

- For the Nam Thu Hotel project, the ratio between the thickness of the liquefied sand layer ($l_{p,liq}$ = 14 m) and the pile length (l_p = 24 m) is 58.3 % and the decrease between the axial ultimate bearing capacity of pile related to the influence of liquefaction potential of the pile and the axial ultimate bearing capacity of pile is 74 % corresponding to the frequency of 1 Hz and 75 % corresponding to the frequency of 2 Hz according to method 4 with the case of the pile tip is inserted into the clay layer. For the General Hospital project, the ratio between the thickness of the liquefied sand layer ($l_{p,liq}$ = 10 m) and the pile length (l_p = 16 m) is 62.5 % and the decrease between the axial ultimate bearing capacity of pile related to the influence of liquefaction potential of the pile and the axial ultimate bearing capacity of pile is 47 % corresponding to the frequency of 1 Hz and 48 % corresponding to the frequency of 2 Hz according to method 4 with the case of the pile tip is inserted into the sandy layer.

- The relationship between the ultimate axial load capacity of the pile due to liquefaction and the oscillation frequency (f) is linear. The degradation difference $\Delta R_{s,liq,4\text{-}5}$ of pile shaft is 56.27 % ÷ 69.80 % corresponding to frequency f = 1 Hz and 75.70 % ÷ 79.21 % corresponding to frequency f = 2 Hz.

- The degradation difference $\Delta R_{u,liq,4\text{-}5}$ of the pile is 13.40 % corresponding to the frequency f = 1 Hz and 14.60 % corresponding to the frequency f = 2 Hz for the pile tip in the sand clay layer, while the degradation difference $\Delta R_{u,liq,4-5}$ of the pile is 2.68 % corresponding to the frequency f = 1 Hz and 4.07 % corresponding to the frequency f = 2 Hz for the pile tip in the sand layer.

The ground acceleration band corresponding to the frequency f = 1 Hz and f = 2 Hz with the oscillation period t = 10 s by Geostudio 2018 software, it is found that the result of the axial ultimate bearing capacity of pile related to the influence of liquefaction potential ($R_{u,liq}$) of pile changes with time t from 0 s to 2.14 s and no changes after time t from 2.14 s to 10 s. Specifically, applying the calculation to the Nam Thu hotel project, at time t = 0.2 s, the max value of the axial ultimate bearing capacity of pile related to the influence of liquefaction potential ($R_{u,liq}$) of pile is 840.9 kN corresponding to the frequency f = 1 Hz and 831.4 kN corresponding to the frequency f = 2 Hz, the time period t from 2.14 s to 10 s, the min value of the axial ultimate bearing capacity of pile related to the influence of liquefaction potential ($R_{u,liq}$) of pile is 714.1 kN corresponding to the frequency f = 1 Hz and 706.7 kN corresponding to the frequency f = 2 Hz. Similarly, applying the calculation to the General Hospital project, at time t = 0.2 s, the max value of the axial ultimate bearing capacity of pile related to the influence of liquefaction potential ($R_{u,liq}$) of pile is 1046.4 kN corresponding to the frequency f = 1 Hz and 1014.9 kN corresponding to the frequency f = 2 Hz, the time period t from 2.14 s to 10 s, the min value of the axial ultimate bearing capacity of pile related to the influence of liquefaction potential ($R_{u,liq}$) of pile is 947.4 kN corresponding to the frequency f = 1 Hz and 898.1 kN corresponding to the frequency f = 2 Hz

- The value of the reliability index (β_T) is approximately equal according to the PP4 method corresponding to the frequency f = 1 Hz, the Boulanger et al. (2004) method, the Fellenius et al. (2008) method and the Muhunthan et al. (2017) method, while the value of the reliability index (β_T) is the smallest according to the Geostudio 2018 method corresponding to the frequency f = 1 Hz.

- According to the proposed PP4, the value of the reliability index (β_T) is 2.533 corresponding to f = 1 Hz and 2.534 corresponding to f = 2 Hz for the Nam Thu hotel project and the value of the reliability index βT is 1.704 corresponding to the frequency f = 1 Hz which is smaller than the value of the reliability index (β_T) is 1.707 corresponding to the frequency f = 2 Hz for the

General Hospital project, the value of the reliability index (β_T) is both in the range (0.5 ÷ 3.5).

CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions

1). Using the Kanai model (1957), an artificial ground acceleration band was established according to the time period T = 10 s corresponding to the geological characteristics of the research area to obtain the base data area to establish dynamic parameters for experiments and simulation calculations. Specifically, the results obtained the appropriate oscillation frequency amplitude is f = 1 Hz ÷ 2 Hz corresponding to the time period T = 10 s.

2). From the results of the cyclic triaxial test according to the stress paths (CTC, CTC-RTE, RTE), the dynamic strength parameters characteristic of liquefaction for sandy soil with the number of cycles n for frequency f = 1 Hz and frequency f = 2 Hz are established as follows: $CSR = -0.064\ln(n) + 0.3868$ for f = 1 Hz; $CSR = -0.034\ln(n) + 0.2309$ for f = 2 Hz; $r_u = 0.0978\ln(n) + 0.6079$ for f = 1 Hz; $r_u = 0.0767\ln(n) + 0.7108$ for f = 2 Hz.

- The relationship between r_u ratio and CSR ratio is nonlinear, the value of CSR ratio decreases and the value of r_u ratio increases corresponding to frequency f = 1 Hz and frequency f = 2 Hz: $r_u = -0.8660CSR + 0.8702$ for frequency f = 1 Hz, $r_u = -2.255CSR + 1.1616$ for frequency f = 2 Hz.

- The value of the degradation resistance factor (k) is smaller while the number of cycle n is larger corresponding to frequency f = 1 Hz and frequency f = 2 Hz, here k is tgφ'/tgφ and n is from 1 cycle to 20 cycle, with $k = -0.098\ln(n) + 0.3921$ corresponding to frequency f = 1 Hz and $k = -0.0767\ln(n) + 0.2892$ corresponding to requency f = 2 Hz. Based on this result, it is possible to add a prediction of the internal friction angle due to the decrease when related to the influence of liquefaction potential (φ') and compare it with Vietnam construction standards (TCVN 10304:2014 standard).

3). Results obtained from applying calculations to two projects

- Calculation results of the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential for typical sandy soil according to the methods by Boulanger et al. (2004), Fellenius et al. (2008), Munhunthan et al. (2017), Geostudio 2018 software and the author's proposed method are similar, but there is a difference compared to the calculation method according to and Vietnam construction standards (TCVN 10304:2014 standard).
- The decrease between the axial ultimate bearing capacity of pile related to the influence of liquefaction potential of the pile and the axial ultimate bearing capacity of pile depends on the ratio between the thickness of the liquefied sand layer ($l_{p,liq}$) and the length of the pile (l_p) or the pile tip inserted into the sand or clay layer. The decrease between the axial ultimate bearing capacity of pile related to the influence of liquefaction potential of the pile and the axial ultimate bearing capacity of pile is greater when the pile tip is inserted into the clay layer and conversely, the decrease between the axial ultimate bearing capacity of pile related to the influence of liquefaction potential of the pile and the axial ultimate bearing capacity of pile is smaller when the pile tip is inserted into the sand layer corresponding to the frequency of 1 Hz and the frequency of 2 Hz.
- The degradation difference $\Delta R_{s,liq,4-5}$ of pile shaft is 56.27 % ÷ 69.80 % corresponding to frequency f = 1 Hz and 75.70 % ÷ 79.21 % corresponding to frequency f = 2 Hz.
- The difference in the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential of the pile with the tip of the pile inserted into the clay layer is greater than the difference in bearing capacity of the pile with the tip of the pile inserted into the sand layer corresponding to the frequency f = 1 Hz and the frequency f = 2 Hz. Specifically, the difference in the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential ($\Delta R_{u,liq,4-5}$) of the pile is 13.40 % corresponding to frequency f = 1 Hz and 14.60 % corresponding to frequency f = 2 Hz for the pile tip inserted into the clay layer, and the difference in the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential ($\Delta R_{u,liq,4-5}$) of the pile is 2.68 % corresponding to frequency f = 1 Hz and 4.07 % corresponding to frequency f = 2 Hz for the pile tip inserted into the sand layer.

- The value of the r_u ratio corresponding to the frequency f = 1 Hz is smaller than the value of the r_u ratio corresponding to the frequency f = 2 Hz for sandy soil layers considering the possibility of liquefaction potential, so the value of $R_{u,liq}$ corresponding to the frequency f = 1 Hz is larger than the value of $R_{u,liq}$ corresponding to the frequency f = 2 Hz according to PP4 method.
- Propose a formula for calculating the axial ultimate bearing capacity of single pile shaft related to the influence of liquefaction potential ($R_{s,liq}$) according to the sandy soil and improve the above formula (related to the influence of the excess pore water pressure ration, r_u) for the sandy foundation in Quy Nhon Gia Lai area, related to the influence of liquefaction potential of the sandy foundation due to earthquakes (M_w = 6.5) corresponding to the frequency of 1 Hz and the frequency of 2 Hz.

2. Recommendations

- Determine the excess pore water pressure ratio (r_u) corresponding to different frequencies (f) for sandy soil according to depth, from which to establish the correlation calculation functions between the excess pore water pressure ratio (r_u) and the standard penetration test index (N_{60}) considering the fine content FC (%) of sandy soil considering the liquefaction phenomenon. In addition, further research is needed for cases such as clay soil and sand clay soil.
- Study the axial ultimate bearing capacity of single piles related to the influence of liquefaction potential in sandy soil corresponding to the frequency (f) change for the sand layers.
- Study the axial ultimate bearing capacity of the pile group, considering the liquefaction capacity of the sand foundation corresponding to the change in frequency f for each sand layer that the pile penetrates, when simultaneously subjected to axial and lateral loads of the pile group.

LIST OF SCIENTIFIC WORKS RELATED TO THE THESIS

1. Hua Thanh Than, Nguyen Ngoc Phuc, Nguyen Van Cong (2017), *Analysis of liquefation capacity of sand in coastal areas Binh Dinh province*, Vietnam Geotechnial Journal, ISSN - 0868-279X, Number 3 - 2017, pp. 51-60.
2. Hua Thanh Than, Nguyen Ngoc Phuc, Pham Thi Lan (2018), *Standard penetration testing and cone penetration testing for liquefaction potential evaluation of saturated sandy soil,*. Vietnam Journal of Construction, ISSN: 0866-8762, No. 2 - 2018, pp. 55-60.
3. Hua Thanh Than, Nguyen Van Cong, Pham Thi Lan (2018), *Standard penetration testing based over time in sand foudation for liquefation potential evaluation,* Vietnam Journal of Construction, ISSN - 0866-8762, No. 11 - 2018, pp. 146-152.
4. Hua Thanh Than, Nguyen Ngoc Phuc, Tran Thi Thanh (2019). *Analysis of the ultimate bearing capacity of single piles in sand foundation of the coastal areas in Binh Dinh province ralated to the affected for liquefaction potential during earthquakes*. Vietnam Journal of Construction, ISSN: 0866-8762, No. 5 - 2019, pp. 161-165.
5. Hua Thanh Than, Nguyen Ngoc Phuc, Tran Thi Thanh, Nguyen Van Cong (2020), *Analysis of the ultimate bearing capacity of single pile over time in sandly soil in Binh Dinh province related to the affected for liquefaction potential during earthquake duration,* Vietnam Journal of Construction, ISSN: 0866-8762, No. 2 - 2020, pp. 16-20.
6. Hua Thanh Than, Nguyen Ngoc Phuc (2020), *Effect of saturated soil in liquefaction sand foundation of the coastal areas in Quy Nhon city Binh Dịnh provice,* Vietnam Journal of Construction, ISSN: 0866-8762, No. 5 - 2020, pp. 39-45.
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10. Ngoc-Phuc Nguyen, Thi-Thanh Tran, Thanh-Than Hua (2018), *Analysis the unit resistance along pile by using logical equations and PDA testing results,* 15th Regional Congress on Geology, Mineral and Energy Resources of Southeast ASIA, GEOSEA 2018, Ha Noi, Vietnam, pp. 468-471.
11. Hua Thanh Than, Nguyen Ngoc Phuc, Tran Thi Thanh (2019), *Effect of excess pore water pressure in saturated sandy soil for evaluating liquefaction poterntial during earthquake duration,* 5th International Conference, Science Engineering and Environment, SEE BANGKOK 2019, ThaiLand, ISBN: 978-4-909106032 C3051, pp. 497-505.
12. Hua Thanh Than, Nguyen Ngoc Phuc, Nguyen Van Cong (2020), *Establishing correlation between dynamic strength parameters and standard penetration test (SPT) index in sandy soil for Quy Nhon city, Binh Dinh province related to the affected for liquefaction potential*, University-level scientific research project - Quang Trung University, Code CS/19/21.